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Optimizing The Design Of Chilled Water Plants In Large Commercial Buildings

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Optimizing the Design of Chilled Water Plants in Large Commercial Buildings

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Biographical Sketch

Dante′ E. Freeland is a second year graduate student from Largo, MD currently pursuing his Master of Science degree in Civil Engineering at North Carolina Agricultural and Technical State University. During his undergraduate career at the same university he was able to obtain a Bachelor's of Science degree in Architectural Engineering, where his concentration was in HVAC design and building energy. In this program he developed a knack for designing all aspects of HVAC in buildings as well as becoming very skilled in the energy analysis of buildings. He took several courses, attended numerous conferences, and held several internships in this field, often taking on leadership roles within the various tasks that came with them. His increasingly strong passion for HVAC design and building energy led him to seek furthering his education to graduate studies. During his graduate career he was able to focus entirely on targeting ways to decrease energy within buildings. This led him to working with his major professor on developing a thesis that would tie in all his previous knowledge into one project. With the completion of this thesis he will be looking to work designing HVAC systems and performing energy analysis of buildings.

Dedication

This thesis is dedicated to everyone that believes in innovation through experimentation. By simply pushing the issue and expanding your knowledge, there is no problem that can withstand the solution the mind dreams up.

Acknowledgements

This thesis paper would not be possible without the backing of my advisor Dr. Nabil Nassif. His passion for his field knows no equals. Dr. Nassif helped me each step of the way, starting with my first steps into his office as a graduate student. By supporting this project and being a constant force pushing for the results of this experiment, he has truly helped me gain a greater understanding of the work ethic of a true engineer. Dr. Nassif your contributions to this work and helping me develop as a future engineer is greatly appreciated.

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Abstract

The design of chilled water plants has a very large impact on building energy use and energy operating costs. This thesis proposes procedures and analysis techniques for energy efficiency design of chilled water plants. The approach that leads to optimal design variables can achieve a significant saving in cooling cost. The optimal variables include piping sizing, chilled water temperature difference, and chilled water supply temperature. The objective function is the total cooling energy cost. The proposed design method depends on detailed cooling load analysis, head and energy calculations, and an optimization solver. The pump head calculations including piping, all fittings, valves, and devices are achieved by using the Darcy-Weisbach Equation and given flow parameters. The energy calculations are done by using generic chiller, fan, and pump models. The method is tested on an existing four-story building located in Greensboro, NC, equipped with a packaged water-cooled chiller. A whole building energy simulation model is used to generate the hourly cooling loads and then the optimal design variables are found to minimize the total energy cost. The testing results show this approach will achieve better results than rules-of-thumb or traditional design procedures. The cooling energy saving could be up to 10% depending on particular projects.

CHAPTER 1

Introduction

1.1 Overview

The development of a software that can optimize the energy usage of the chilled water plant is a tool that will have a significant effect on building energy consumptions and costs. Through rigorous programming this software has begun to take form and show the great benefits expected from optimizing several of the key components of the chilled water plant. By simulating the energy load of a known building and applying it to the aforementioned program, an experiment was created to test how effective a chilled water plant optimization program could really become.

1.2 Purpose of Research

The chilled water plant in a commercial building is responsible for up to 30 percent of energy consumption of the building. With an increased emphasis by the government to push for more sustainable energy efficient buildings, addressing this issue is critical to achieving this goal. In targeting the chilled water plant as a place to lower energy usage, the design that is used in creating the system was highlighted as the main problem that should be addressed. The design of the chilled water plant has been largely based around rule of thumb numbers rather then optimal design calculations. This in turn has left a void for a way to optimize the design of a chilled water plant. One way to fill this void would was to create a program that could handle the demand of optimizing the design of a chilled water plant as well as show the energy savings that the optimal design created. This program would be a great teaching mechanism as well as a beneficial tool for practical purposes. Students will be able to use this tool in the future for design projects and companies that are considering designing a chilled water plant will be able to do so very efficiently. Most importantly the optimization program will address the severe need to decrease the energy usage within buildings. This will create a standard that can be followed in the future that will benefit the building energy field greatly.

1.3 Research Questions

Before starting this research there were numerous factors that needed to be addressed in order to create an efficient optimization program. These factors will serve as the foundation on which the program will stand. The factors include:

1.3.1 What design variables should be considered?. The chilled water plant is a large system that has many complex components. This makes the decision on what specific areas of the system to focus the search to decrease energy on difficult. One major factor to energy consumption as well as cost is the sizing of pipes within the chilled water plant. With larger pipes there is an increase in energy due to more pressure being needed to move the water through the system of piping. The cost comes into play as well, due to more material being used for larger the pipes are sized. In order to decrease the size of the pipes in the chilled water plant, there must be a way to lower the pressure. This can be accomplished by introducing the chilled water temperature difference as another variable to be used in optimizing the chilled water plant. The chilled water temperature difference directly affects the pipe sizing. The chilled water temperature difference is inversely proportional to the pipe sizing, so if the temperature difference is raised the pipe sizing will decrease. With the pipe sizing and chilled water temperature difference working to decrease energy used by the chilled water plant, there was one additional variable that was chosen to be used in the optimal design program. This variable was the chilled water supply temperature. The chilled water supply temperature directly affects the energy usage from the chilled water plant. A higher chilled water supply temperature translates into a decrease in energy used to cool the supply water down to a lower temperature. In finding these variables, there are targets that can be experimented with to find an optimal design for chilled water plants.

1.3.2 What equations will be needed?. The chilled water plant optimization program is a math-based program. The purpose of the program is to make calculations that will demonstrate the optimal design of a chilled water plant. This will involve introducing several different equations into the optimization program. These equations will have to address the different components of a chilled water plant including: water side, air side, and energy equations. The water side equations will consist of the Darcy-Weisbach equation for the pressure and head loss through the piping and an equation to calculate water flow in gallons per minute (GPM). The air side equation will consist of an equation to calculate air flow cubic feet per minute (CFM). Finally, the energy equations will consist of equations that calculate different energy usages in kilowatt-hours per year. These equations will be embedded within the optimization program to help produce an accurate calculation of the optimization of the chilled water plant.

1.3.3 What type of approach for the program should be used?. The chilled water plant optimization program was designed for the purpose of solving a major energy problem within buildings. In designing the program, an approach needed to be decided on in order to allow the program to function as more than a calculator. With the goal being to find the optimal design of a chilled water plant, the program needed to have a feature that could search through a very large amount of data and choose the optimal results. This necessity led to the decision to use Matlab which has a genetic algorithm used to achieve the most affective operating system for the program to function. The genetic algorithm is designed to be an efficient tool for optimization and searching for specific results. Combining the Matlab genetic algorithm along with the equations and variables in the optimization program make for a strong combination that will allow accurate results when tested.

1.4 Scope and Significance of Research

With the steady decrease of fossil fuels, there has been a steady increase in sustainable building demand. This demand has caused for innovative measures to be taken in the design of buildings. The design of a chilled water plant optimization program fills an immediate need to one of a building's biggest problems, energy consumption. An optimization program that saves on energy consumption also saves financially. In unsteady economical times, saving money has become a major issue to be addressed before any building process can even begin. These factors show how major problems plaguing the building energy industry can be offset through innovation. In creating a tool that is reusable and demonstrates different changes that can be made to save energy and money, a new way of designing building systems can be spawned. With future advancements to technology and to the optimization program a future of continued fiscal and energy savings is within sight.

1.5 Conceptual Framework and Methodology

The foundation of which this research stands upon, is the idea that a vast amount of energy can be saved simply by focusing on the details of a chilled water plant for optimization purposes. The sequence that follows this idea starts from variables that have been proven to have an affect on energy consumption all the way to developing an optimization program to develop these same variables. This will be carried out by, investigating the characteristics of different processes that offer ways to decrease energy usage within chilled water plants. In doing this, different software and known parameters will come together to add validity and a starting point for the chilled water optimization program to bring energy and cost savings to real world applications.

1.6 Limitations

The limitations of this project are based around the flexibility of which the design variables can be pushed. The sizing of pipes, chilled water temperature difference, and chilled water supply temperature all have directly and indirectly proportional relations with energy consumption and costs. When you change one of the variables, it sets off a sequence of adjustments that either contributes to the optimization of the chilled water plant or further takes away from the non-optimal design. This important factor causes the testing range of each design variable used within the optimization program vary greatly. In order to find optimal results for the chilled water plant, parameters were set for each of the design variables to follow. This limited the range of the design of the system, but also created a medium level to be reached for necessary optimization.

1.7 Thesis Organization

This thesis paper is broken down into five chapters. The first chapter is an introductory chapter that brings to the forefront that the thesis topic is developing an optimization program for the chilled water plant of large commercial buildings. The second chapter provides a literature review for the articles that were vital to gaining the understanding needed to produce results with the optimization program. The third chapter sheds light onto how the program was developed and operated to produce the optimal design variables. The fourth chapter gives an analysis of the program and the optimal results compared to a baseline using non-optimal outputs. The fifth and final chapter gives a discussion of the results of the optimization program as well as gives insight to future advancements that can be made to the program.

1.8 Definitions

A. eQuest: is a department of energy software designed to allow you to perform detailed analysis of today's state-of-the-art building design technologies using today's most sophisticated building energy use simulation techniques but without requiring extensive experience in the "art" of building performance modeling

B. Chilled Water Plant: a distribution system that that provides chilled water for air conditioning in buildings

C. Chilled Water Temperature Difference: the difference between the chilled water return and supply temperatures

D. Chilled Water Supply Temperature: the chilled water that is supplied for cooling in the chilled water plant loop

E. Head Loss: the pressure lost in a piping system

F. Cubic Feet per Minute (CFM): the rate at which air is flowing through a ducted system

G. Gallons per Minute (GPM): the rate at which a liquid is flowing through a piped system

H. BTU/HR: a measurement for the HVAC energy load and it is the amount of energy needed to cool or heat one pound of water by one degree Fahrenheit per hour

I. ASHRAE Climate Zones: a breakdown of the regions in the United States based off of climate

J. Matlab: is a high-level language and interactive environment for numerical computation, visualization, and programming

CHAPTER 2

Literature Review

2.1 Introduction

The articles summarized within this chapter were crucial in providing information needed to develop the data within the chilled water plant optimization program. This literature made for great resources that allowed for clear conclusions to be developed on certain aspects of the model programming. Overall, reading through articles specified in the related topics within this research allowed for a greater understanding of the data being tested.

2.2 Optimizing Design and Control of Chilled Water Plants (Part 1)

This article goes into detail about how to efficiently select a chilled water distribution system. The covered distribution types include: Primary-Only-Single Coil, Primary-Only-Single Chiller, Primary-Only-Multiple-Chillers-Few Coils With Similar Loads, Primary-Only Variable Flow, Primary-Secondary, Primary-Distributed Secondary, and Primary-Coil Secondary. The Primary-Only-Single Coil is the first distribution type examined within the article. This distribution type was limited by only being able to function with one coil air-handling units, but could have any amount of chillers serving the system and have any size load. The less complex design techniques supported not having any control values throughout the system because of constant-value pump pushing chilled water through the system. This along with controlling the supply air temperature by resetting the temperature of the supply water temperature to as high a temperature as possible, made for a design that could be used for different situations with these variables. The concern about high humidity within a building based on the chilled water temperature being raised in this design was negated due to the fact that the supply air temperature setpoint determines the amount of humidity within the building (Taylor, 2011 a).

The Primary-Only-Single Chiller distribution type is compatible with an air-handling system with more than one coil but only one chiller can be used for this method. This distribution type only serves small loads less then or equal to 100 GPM (Taylor, 2011 a) and is a variable flow system. The installation of two and three-way control valves aid in keeping the minimum flow needed by the chiller, which is critical when working with more then one coil (Taylor, 2011 a). The Primary-Only-Multiple-Chillers-Few Coils With Similar Loads distribution type has few coils serving similar loads, which requires more then one chiller. This distribution type is for smaller spaces and thus serves small loads less then or equal to 100 GPM (Taylor, 2011 a). Three-way control valves are the only valves used to control due to the additional pressure added by multiple chillers. Concern was raised about the ability of the system to meet flow demands under certain conditions. This concern was addressed by making an adjustment to the operation of the pumps. Ideally this distribution type would be used when coil loads differ in the same proportion. The Primary-Only Variable Flow and Primary-Secondary distribution types have very similar concepts. They either have many coils serving similar loads or any serving dissimilar loads. They also serve small loads less then or equal to 100 GPM and our supported by more than one chiller only using two-way control valves (Taylor, 2011 a). These two distribution types vary in the decision for the Primary-Only Variable Flow to use a combination of VFD primary pumps with a bypass valve to ensure minimum flow rates through the chiller while Primary-Secondary uses a combination of primary pumps along with a common leg and VFD secondary pumps to ensure minimum flow rates through the chiller. The advantages that come as a result of using the Primary-Only Variable Flow consist of: lower first costs, less plant space required, reduced pump peak power, and lower pump annual energy usage (Taylor, 2011 a). The advantages that come as a result of using the Primary-Secondary consist of: a less complex system without bypass control and without having to stage the chillers (Taylor, 2011 a). The Primary-Distributed Secondary distribution type serves more than one coil load and the size of the coils support massive loads needed for a large campus. This distribution type also uses two-way control valves and supports any number of chillers within the system (Taylor, 2011 a). The Primary-Distributed Secondary system is considered the best option when designing the central plant for a large collection of buildings that will produce sizeable loads. The advantages to this distribution type compared to other primary-secondary system include: reductions in pump horsepower, having a self-balancing system because of the speed controls on the secondary pumps, the elimination of excess pressure of the control valves near the central plant, reduction of pump energy, eliminating bridge connections, and decreasing energy costs (Taylor, 2011 a). The disadvantages however include: an increase in expansion tank pressurization and higher initial costs. The last distribution type the article covers was the Primary-Coil Secondary. This distribution type is used in systems that serve more than one large coil, which is sized to handle greater or equal to 100 GPM (Taylor, 2011 a). There are no control valves within this system and it can be used with any amount of chillers. This system is considered ideal for large single air-handling systems using distributed variable speed driven coil secondary pumps. The advantages of this distribution type include: a reduction in pump motor horsepower, being self-balancing, a reduction in pump energy used, and being able to immediately control system flow (Taylor, 2011 a). The disadvantages however include: a design flaw that requires expensive multistage pumps and an increased exposure to equipment failure due to the pump and VFD being more inclined to fail then a control valve (Taylor, 2011 a). Overall, these different distribution types all serve as a reliable system to base the central plant around when their necessary parameters are needed. This article went into great detail in expressing how each system should be used and creates a method of selection that can be followed to select the correct chilled water distribution system.

Table 1

Chilled Water Distribution System (Taylor, 2011 a)

Application	Coils/Loads Served	Chillers	Size of Coils/Loads Served	Control Values	Recommended Distribution Type
1	One	Any	Any	None	Primary-Only-Single Coil
2	More Than One	One	Small (≤ 100 gpm)	2-Way and 3-Way	Primary-Only-Single Chiller
3	Few Coils Serving Similar Loads	More Than One	Small (≤ 100 gpm)	3-Way	Primary-Only-Multiple Chillers-Few Coils With Similar Loads
4	Many Coils Serving Similar Loads or Any Serving Dissimilar Loads	More Than One	Small (≤ 100 gpm)	2-Way	Primary-Only or Primary-Secondary
5	More Than One	Any	Large Campus	2-Way	Primary-Distributed Secondary
6	More Than One	Any	Large Coils (≥ 100 gpm)	None	Primary-Coil Secondary

2.3 Optimizing Design and Control of Chilled Water Plants (Part 2)

This article details the design of condenser water systems. Three common piping arrangements for condenser water pumps are explored along with several variables that affect the condenser water system design. These variables include: refrigerant head pressure control, minimum flow rates, piping for waterside economizers, and variable speed condenser water pumps. This article gives insight on how these components come together create an efficient system. The three options of common piping arrangements for condenser water pumps consisted of the following: an Option A of dedicating a pump for each condense, an Option B of providing a common header at the pump discharge and two-way automatic isolation valves for each condenser, and an Option C of providing a common header with normally closed manual isolation valves in the header between pumps (Taylor, 2011 b). These options all have their own design advantages that make them unique from one another. The advantages in Option A consist of: being able to custom select the pump for the condenser it serves, having pump controls directly linked to the chiller, and pump failures not resulting in multiple chiller trips (Taylor, 2011 b). Being able to custom select the pump for the condenser it serves allows for accommodations to be made for pressure drop and flow rates, which can reduce energy. Having pump controls directly linked to the chiller makes for instantaneous reactions when start and stop signals are made. Having pumps directly responsible for each chiller allows one pump's malfunction not to result in a total system failure. In the second option, Option B, the advantages consist of: pumps not being assigned to a specific chiller, an easier inclusion of a standby pump, versatility of isolation valves, and an easier integration of a water-side economizer (Taylor, 2011 b). When pumps are not assigned to a specific chiller it allows for a single pump to account for multiple chillers in the case of equipment failure. Having an easier inclusion of a standby pump saves financially and in system downtime because of the rigorous installation process. The versatility of isolation valves is beneficial because they can double as head pressure control valves. The third and final option, Option C, has the following advantages: has the advantages of Option A without its setbacks, manual pump isolation, and is less expensive then a similar Option B. Having the advantages of Option A without its setbacks makes it a viable system to consider when in the design process. A manual pump isolation valve is a valuable asset when a system experiences a pump failure because this type of breakdown in equipment requires a manual influence to get back to normal operation (Taylor, 2011 b). These options for piping arrangements for condenser water pumps are all systems to be considered for design based upon the required tasks of the central plant. The Refrigerant Head Pressure is an essential part of the condenser water system. This head pressure is usually quite high when in normal operation, but can lower with cold water temperatures at start up and with the integration of waterside economizers. When trying to avoid low refrigerant head pressure it is important to consider the options of three-way bypass valves, having variable speed drive on pumps such as in Option A and C, and using isolation valves as head pressure control valves such as in Option B (Taylor, 2011 b). These options all help to stabilize the refrigerant head pressure, thus keeping the operating correctly. Maintaining minimum flow rates is a necessity when water is moving through the cooling towers. There were three main solution designs for keeping this minimum flow rate that prescribed: selecting tower weir dams and/or nozzles to allow one pump to serve all towers, installing automatic valves on only supply lines, and installing automatic isolation valves on both supply and suction line (Taylor, 2011 b). The decision to select tower weir dams and/or nozzles to allow one pump to serve all towers was considered to be the most energy efficient and fiscally responsible option to maintain a minimum flow rate. The ability of this selection to reduce fan speed and avoid using control valves makes it the first option that should be considered when possible. When there are many chiller towers to be accounted for within a design, installing automatic isolation valves to just the supply lines or both the supply and suction lines becomes the best option. When these valves our added to both the supply and suction line, there is more exposure to valve failure as well as an increase in cost due to installation expenses. Waterside Economizers are used to take load off the chillers by supplying chilled water without or reduced mechanical refrigeration (Taylor, 2011 b). They are typically less expensive then airside economizers and are commonly used in floor-by-floor air handlers in high-rise office buildings and computer room air handlers for a large data centers. When introducing this component into a condenser water system design, it must be integrated into the piping arrangements. With this integration, it is vital that the waterside economizer have a similar pressure drop to the chiller so the system will not malfunction. The use of variable speed drives has increased over the years due to the decreased energy consumption seen when they are in use. Pairing variable speed drives with condenser water pumps has been practice that has been questioned due to little evidence of them being cost effective and the required control logic is not self-apparent (Taylor, 2011 b). With these questions came a study that showed that variable speed drives with condenser water pumps are life-cycle cost effective as long as optimum control sequences are used. The optimization was shown to be critical when a chilled water plant with ideal controlled sequences in one city was tested in another location. The energy consumption was significantly greater then the optimal control sequence designed for the tested location. This shows that putting an emphasis on the control of the variable speed drive is key in integrating it with condenser water pumps.

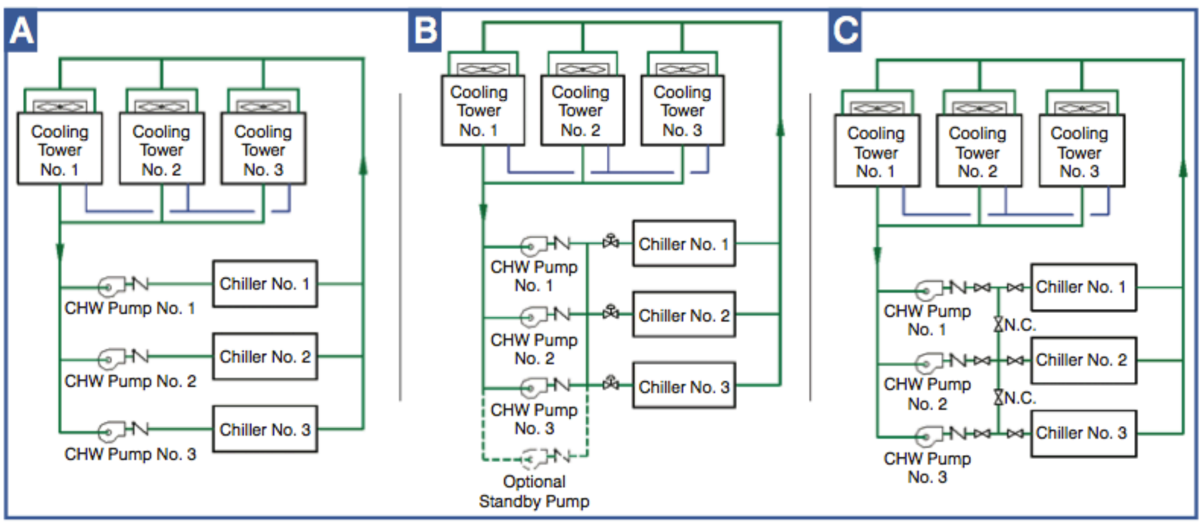

Figure 1. Condenser Water Pump Piping Options (Taylor, 2011 b).

2.4 Optimizing Design and Control of Chilled Water Plants (Part 3)

This article details the process of selecting the proper pipe sizing along with optimizing the chilled water temperature difference. A concentration is placed upon the usage and size of pipe selection, optimizing chilled water design temperatures, and optimizing condenser water design temperatures. These variables play a vital role in the design and energy consumption of the chilled water plant. Pipe Sizing has traditionally been a rule of thumb calculation that determines what pipes will be incorporated into the chilled water plant. This approach however, is not the most efficient way to achieve an optimal piping design. The use of a life-cycle cost analysis (LCCA) is both simple to use and can provide optimum sizing results for the anticipated piping system. The ease of using spreadsheets which layout all of the different pipe sizing options with the usage limitations already calculated, make for an affective tool when analyzing a fully laid out piping design. In pursuit of selecting the proper pipe sizing, optimizing chilled water design temperatures come into play. The chilled water temperature difference and chilled water supply temperature greatly affect the components of the chilled water plant. Designing for the exact temperatures of each creates conflicts of whether to drop or raise temperatures in order to achieve optimal energy savings. The chilled water temperature difference has both positive and negative reactions when increased or decreased. When increased, the flow needed for the chilled water plant decreases and smaller size pipes are required (Taylor, 2011 c). With smaller pipe sizes, cost in material is saved as well as pressure within the system is lowered. When the pressure within the piping system is lowered a smaller pump can be used and pump energy consumption is lowered (Taylor, 2011 c). The drawback in increasing the chilled water temperature difference is a pressure drop through the coil. In order for this pressure drop to be accounted for, extra rows must be added to the coil and an increase in fan power must be made to accommodate (Taylor, 2011 c). When the chilled water supply temperature is increased, the energy consumption of the chiller decreases helping make up for the increase in fan energy. Finding the balance of changing these temperatures allows for an optimal design to be designed for the chilled water plant. The selection of condenser water temperature differences is more difficult then selection of chilled water temperature difference. This process becomes difficult based on the condenser water temperature great affecting both the chiller and cooling tower. A high condenser water temperature difference results in lower pump energy consumption, due to the decrease in pipe size needed, and a lower cooling tower energy consumption (Taylor, 2011 c). This is compared to a low condenser water temperature difference resulting in lower chiller energy consumption. The trade off between raising and lowering the temperature is difficult to assess but is necessary in order to create an optimal design.

Table 2

Impact on First Costs and Energy Costs of Chilled Water Temperature Difference (Taylor, 2011 c)

	ΔT	
	Low	High
Typical Range	8°F	25°F
First Cost Impact	Smaller Coil	Smaller Pipe Smaller Pump Smaller Pump Motor
Energy Cost Impact	Lower Fan Energy	Lower Pump Energy

2.5 Total Cost of Ownership For Air-Cooled and Water-Cooled Chiller Systems

This article goes into the detail of the how the total cost of operating air-cooled and water-cooled chiller systems can be estimated. The cost analysis was taken to represent the systems in several different ASHRAE climate zones over an expected life-cycle of 20 years. The total cost was based of three parameters: energy cost, installed cost, and maintenance cost. The energy cost was based upon calculating the energy used on air-cooled and water-cooled chillers ranging from 100-500 tons (Naguib, 2009). The annual energy cost was calculated over 600 simulations in order to achieve accurate results. The installed cost was simply based upon modular chilled-water systems to achieve the desired outcomes. The maintenance cost was the final major cost simulation. In order to estimate these costs, previous maintenance contracts were used to determine what typical costs should mirror. With these costs tabulated together, the air-cooled chiller ended up having a lower total cost over the systems life-cycle even though it varied in which parameter cost the most. An emphasis was made that one must look beyond these costs. There are numerous hidden cost such as, increase in labor and water availability that can greatly increase the total cost of owning the air-cooled or water-cooled chiller system (Naguib, 2009). These costs should be assessed in order to gain a greater understanding of what the financial burdens will truly be on the system.

2.6 Sizing Pipe Using Life Cycle Costs

This article addresses the common use of rule of thumb calculations to design the piping systems of chilled water plants. The problem of using this method to design the piping systems is that it leaves a great risk for a large amount of human error within the estimations needed for design. This is addressed within the article by introducing a pipe sizing Excel spreadsheet developed as a part of the Cool Tools Chilled Water Plant Design Guide. This basic functions of this spreadsheet are: to size pipes based on based on a balance between first costs and future energy costs with optimal velocity for erosion and noise generation and to produce all pump head calculations (Taylor, 2006). The spreadsheet operates by calculating the optimal pipe sizing and energy usage that can be used within the specified velocity limits. The optimal pipe sizing portion of the spreadsheet is regulated through user inputs of variables needed to design the system and includes a cost database of hydronic system components. The energy usage portion of the spreadsheet evaluates the pressure drop and pump efficiency that is needed within the piping system. The pipe velocity limits within the spreadsheet are essential to design. These limits are factors of both noise and erosion caused by the velocity of the liquid flow through the piping system. With the effectiveness seen in the spreadsheet's results, it was used in an addendum to ASHRAE standard 90.1-2007 to establish pipe sizing limits. Based on the article, "the limits were determined using the piping spreadsheet along with the following inputs: 100 ft (30m) of straight pipe; ten 90° elbows; six straight flow-through tees; our ball (≤2 in. [51 mm]) or butterfly valves (>2 in. [51 mm]); one wye strainer; one silent check valve; average water temperature of 50°F (10°C); no limits for noise or erosion; and first costs are based on national average from 2008 RS Means Mechanical Cost Data." (Taylor, 2006). The completion of the addendum to ASHRAE 90.1-2007 also includes the new life cycle cost analysis standards based upon the pipe sizing limitations. With the development of tools such as the optimal pipe sizing spreadsheet, non-optimal design methods can start to be abandoned for more economical and energy saving approaches.

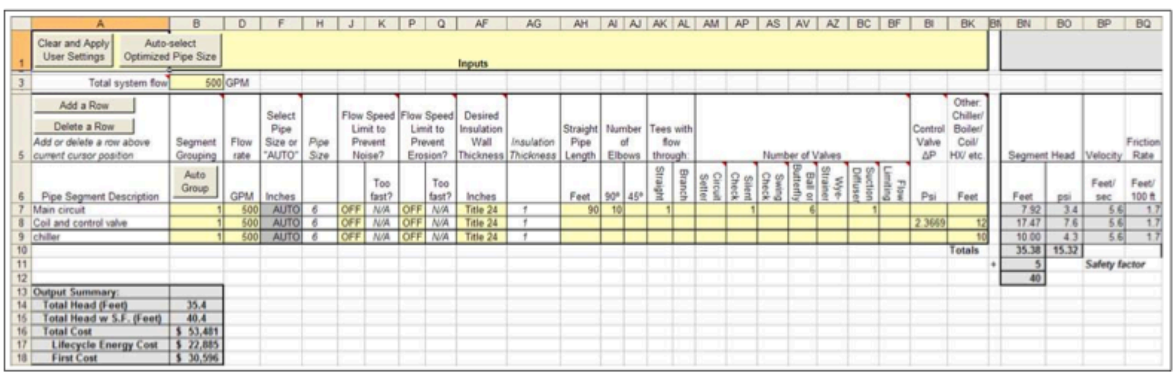

Figure 2. Example of chilled water plant spreadsheet (Taylor, 2006).

2.7 Easy-to-Use Methods for Multi-Chiller Plant and Cost Evaluation

This article addresses the need to consider life cycle cost analysis for central water plants rather then just a simple payback approach. The factors in the life cycle costs included purchase costs, maintenance costs, and energy consumption costs (Duda, 2012). Through life cycle cost analysis, all of these costs can be accounted for in a way that will allow comparisons to be made about which system will provide the most value over the equipment lifespan. In order to test this theory, a spreadsheet was created as a tool to analyze different scenarios to determine which system would be more cost affective over the life of the chilled water plant. The key input components to this spreadsheet included: quantity of chillers and their operating power consumption, quantity and power consumption of primary chilled water pumps, quantity and power consumption of secondary chilled water pumps, quantity and power consumption of condenser water pumps, quantity and power consumption of cooling tower fans, electric demand and consumption charges, makeup water for cooling towers, and natural gas consumption and demand charges (Duda, 2012). This input data was used to analyze the cost of operating different chilled water plants and the output data gave an annual cost the energy consumption. The output data taken from this spreadsheet was imported into a sample life cycle cost spreadsheet that allowed for an analysis of the different chiller plant selections. This gave a clear answer to the most affective option when looking to select the most cost friendly system. The information compiled between the spreadsheets provide insight into the hidden costs of selecting a chilled water plant system to build, showing it to be a creative tool for understanding life cost analysis.

2.8 Why Change the Chilled Water Temperature Range?

This article focuses on evaluating the usefulness of increasing the chilled water temperature difference. The common change seen with increasing this temperature difference can be directly witnessed between the pump energy and pipe installation savings. The article places an emphasis on not settling with these two positive outcomes from increasing the chilled water temperature difference because this increase affects the entire HVAC system. The affects caused by the increase in temperature difference within the chiller, cooling coils, and condensers were all analyzed. The efficiency of a chiller is greatly affected by its compressor lift. The compressor lift is defined as the difference between the condition the refrigerant boils and the condition the refrigerant condenses (Crowther, 2002). The compressor lift of the chiller positively affects its efficiency with the increase of the chilled water temperature difference only when the chilled water supply temperature is constant. This case was also the same for the condenser. Increasing the chilled water temperature creates a dilemma in the design of the cooling coils. The increase will create a need for additional rows to be added to the coils which causes another need for lager fans motors to account for the increase in air pressure drop (Crowther, 2002). The conflict created by increasing the chilled water temperature demonstrated that there must be a balance between the increases and decreases made within a chilled water plant. The conflict also showed that there was "no single best solution" (Crowther, 2002) for determining the best methods to practice optimal chiller operation.

2.9 Model Based Building Chilled Water Loops Delta T Fault Diagnosis

This article discusses the issue of low chilled water temperature differences in the chilled water plant known as low delta-t syndrome. A low chilled water temperature difference in a chilled water plant can lead to an increase in energy consumption. This rise in energy consumption can be contributed to an increase in pump and chiller power trying to account for the low temperature difference. The causes for low delta-t syndrome were analyzed in three categories: causes that can be avoided, causes that can be resolved but may not result in energy savings, and causes that cannot be avoided (Wang, 2012). In order to gain solutions for these causes a case study for a building on the campus of Texas A&M University was conducted. A cooling coil model was created to analyze the difference in how the system should operate compared to the actual measured data from the site. The results from the cooling coil model showed a positive chance to improve the chilled water temperature difference in the case study building. The main avoidable cost observed was a lower discharge air temperature set point but could be improved by optimizing cold deck air temperature set point (Wang, 2012). The results of the cooling coil model also indicated that there may either control valve leakage or control issues along the pipes. This information is critical in assessing the low delta-t syndrome within a system.

2.10 Optimum Operating Temperatures

This section from the book Energy Efficiency Manual focuses on the benefits from keeping the chilled water supply temperature as high as possible. High chilled water supply temperatures have been proven to provide large amounts of energy savings in the chiller. This is possible because the only limit to raising the temperature is the demand needed by the cooling load (Wulfinghuff, 1999). This allows chillers with typically lower design supply temperatures to raise them to achieve energy savings. With this raise in supply temperature comes energy questions in the pump and fan energy usage of the system. The fan and pump energy consumption may be raised in order to lower the chiller energy usage, but typically more energy is saved in the chiller then lost in the fans and pumps (Wulfinghuff, 1999). Although it has been shown that keeping the chilled water supply temperature as high as possible creates energy savings for the chiller, the task of maintaining this temperature is a problem in its own right. There were two methods to maintain the chilled water supply temperature: manual and automatic controls. The manual controls involve physically changing the settings of the supply temperature. This main weakness of this control however, is in its inability to track continuously changing cooling load (Wulfinghuff, 1999). The automatic controls are preferred over manual because they don’t require the physical maintenance of having someone change the set points when necessary. There is a challenge however, in designing the automatic controls to maintain the most efficient relationship between the chilled water temperature and the cooling load

(Wulfinghuff, 1999). Without overcoming this challenge there will be missed opportunities to save energy within the chiller.

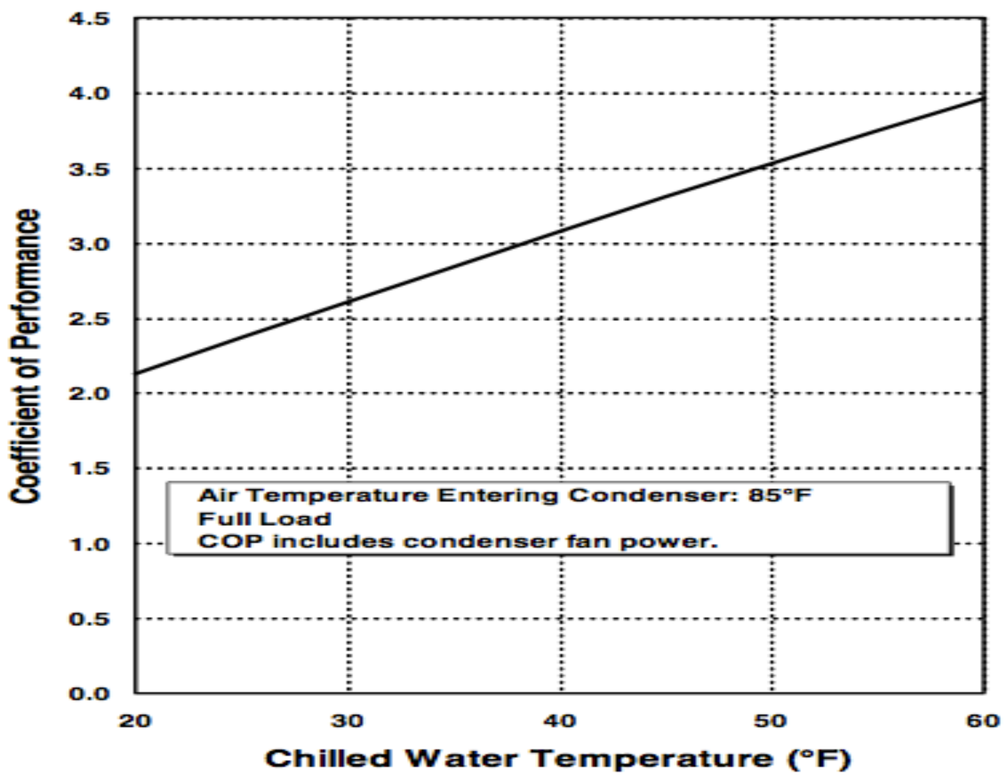

Figure 3. Chart showing how chiller efficiency is improved with higher chilled water supply temperatures (Wulfinghuff, 1999).

2.11 Optimizing Existing Data Center Chilled Water Plants

This article discusses the different methods used to optimize the chilled water plant in existing data centers. The factors that are considered when trying to optimize the chilled water plant included: evaluating system setpoints, assessing proper system loads, and validating operating sequences. In evaluating system setpoints, it is critical to adjust the setpoints to the demand of the load as needed. This is demonstrated in an example where a space that ranges from 72°F to 77°F has a recommended increase in chilled water supply temperature from 45°F to 50°F (McKenna, 2013). When assessing the proper system loads it is important to understand both the space and outdoor climates. These factors play a vital role in determining the limits that can be pushed in the design of the chilled water plant. The validation of the operating sequences comes the chilled water flow rates and chiller operation must be assessed. The chilled water flow rates can be affected greatly by the system having low chilled water temperature differences. It is said that chillers can be limited up to 75% of their design capacity because of this factor (McKenna, 2013). This problem also affects the flow directly by causing the pump energy to increase, making overseeing the system operation even more important. The proper operation of chillers in large chilled water plants is critical to maintaining energy savings. For these large chilled water plants, it can be more beneficial to run more then one chiller to meet demand loads as long as its efficiency savings outweigh the additional pump energy consumption (McKenna, 2013). This balance needed for operating an efficient chilled water plant shows why a constant assessment of how the system is working is needed. With proper assessment and operations, the chilled water plant of data centers can be successfully optimized.

2.12 Energy Impacts of Chilled-Water-Piping Configuration

This article gives an energy analysis of the three basic configurations of a chilled water piping system. These configurations include: constant primary flow (CPF), constant primary flow/variable secondary flow (P/S), and variable primary flow (VPF). The CPF configuration is considered the most basic of the three and is typically used in smaller chilled water plants. The advantages said to be gained by using this configuration included the following: minimized equipment room space due to only having one set of chilled water pumps, low installation costs for constant speed pumps over variable-speed drives, and simple control and system operation (Hubbard, 2011). These advantages help make this configuration a cost efficient system when being installed. The main disadvantage of this configuration exists past the lower installation cost and into the operating costs over the lifetime of the chilled water plant. With constant speed pumps, any time a chilled water plant is operating the pumps are running at full flow regardless of whether the load requires it (Hubbard, 2011). The P/S configuration is divided into primary and secondary loops. The P/S configuration's main difference in comparison to the CPF configuration is its secondary loop is used to control the varying flow and keep a constant chilled water temperature difference rather then the exact opposite in the CPF. The main advantage of the using the P/S configuration consists of the use of variable speed drives on secondary pumps, significantly reducing pump energy consumption in the secondary loop (Hubbard, 2011). This reduction is said to produce as much as 50-60% in energy savings compared to the CPF configuration (Hubbard, 2011). The main disadvantages lie in high installation costs and a potential chance for low delta-t syndrome due to its use of two-way valves. The VPF configuration is similar to the P/S configuration but differs from it having only a primary loop and using variable speed drives on the main chilled water pumps. Having variable speed drives on the main chilled water pumps allows for varied flow throughout each component of the chilled water plant loop. The advantages that come with selecting the VPF configuration are as follows: minimized equipment room space due to only having one set of chilled water pumps, installation cost between CPF and P/S configuration, less installation labor then P/S configuration, less pump energy consumption, better pump operating efficiencies (Hubbard, 2011). The main disadvantages to VPF configuration lie in its complex operation and potential chance for low delta-t syndrome due to its use of two-way valves. Even with these disadvantages the VPF configuration was considered to have the greatest energy saving potential of the three configurations.

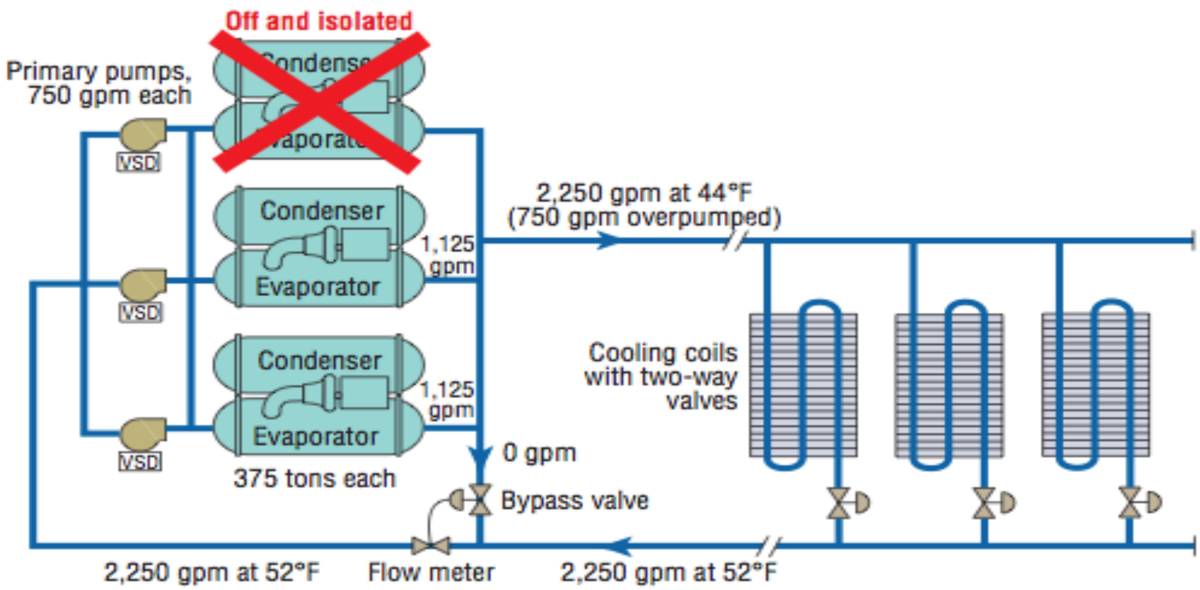

Figure 4. Variable Primary Flow (VPF) configuration (Hubbard, 2011).

2.13 Fluid Piping Systems

This section from this best practice manual was used to analyze the fundamentals of designing pipe flow. The main categories covered in this section included the following: physical properties of fluids, types of fluid flow, and pressure loss in pipes. The physical properties of fluids assessed were the density, viscosity, and Reynolds number. The density was defined as the mass per unit volume of the fluid and is generally measured in kg/m3 (Cengel, 2010). The viscosity was defined as the ease with which the fluid flows (Cengel, 2010). These two properties are critical in determining the Reynolds number, which is defined as the ratio of the dynamic forces of mass flow to the shear resistance due to fluid viscosity (Cengel, 2010). The density and viscosity, along with pipe diameter and velocity combine to create this equation. The main types of fluid flow through pipes are laminar and turbulent flow. Laminar flow consists of flow moving with little velocity and movement through pipes, while turbulent flow moves with high velocity and with disordered movement through the pipes. These fluid flows are used to analyze what piping design is needed for a system. The pressure loss in pipes is calculated through an equation known as the Darcy's equation. In this equation: the friction factor of the inside of the pipe, pipe length, flow velocity, gravitational constant, and pipe diameter are used to find a pressure loss through the pipes that needs to be accounted for in the system (Cengel, 2010). Darcy's equation is related to the Reynolds number and the latter can be substituted into the equation. Knowing these pipe sizing fundamentals is critical before designing any piping system.

$$h_f = \frac{fLu^2}{2gd}$$

Where:
L = Length (m)
u = Flow velocity (m/s)
g = Gravitational constant (9.81 m/s^2)
d = Pipe inside diameter (m)
h_f = Head loss to friction (m)
f = Friction factor (dimensionless)

$$Re = \frac{\rho \times u \times d}{1000 \times \mu}$$

Where:
ρ = Density (kg/m^3)
u = Mean velocity in the pipe (m/s)
d = Internal pipe diameter (mm)
μ = Dynamic viscosity (Pa s)

Figure 5. The Darcy and Reynolds number equations (Cengel, 2010).

2.14 Genetic Algorithms: An Overview

This article discuses the history and usefulness of genetic algorithms. Genetic algorithms were described and developed by John Holland as a way to understand the phenomenon of evolution in nature and apply it to computer systems (Mitchell, 1995). The aspect of evolution in problems that require a lot of searching to gain answers was a main focal point in developing genetic algorithms. The idea that all of the different outcomes of a problem could be solved through the evolution of a solution changed the thinking of how to solve a problem. By having one solution branch off into several different solutions in an ongoing pattern created a way to solve complex problems. In the development of computer systems for genetic algorithms question were brought up on how exactly they work. Genetic algorithms are complex search programs that work by assessing an objective function and then sorting through the parameters needed to achieve this objective function. Several outcomes are formed from the initial parameters used and the system evolves the solutions through different generations until an optimal solution is found. This vigorous search for the optimal results to problems makes genetic algorithms effective optimization tools.

CHAPTER 3

Program Development

3.1 Introduction

The development of the chilled water plant optimization program was developed in several stages. Each of these stages worked as pieces to a whole that led to one operational program. The integration of eQuest, Matlab, and Excel provided a strong platform on which the program to operate. The process of this operation is detailed in this chapter, showing the various sections of program taking place in order to reach optimal outputs.

3.2 Chilled Water Plant Optimization Program

The optimization program was designed to create an analysis of the energy consumption used within a large commercial building's chilled water plant. The components that make up the chilled water plant however, each has their own complexities. These complexities were accounted for by creating smaller programs within the optimization program. These smaller programs consisted of: a chilled water plant model, a chiller model, and a whole system model. The diagram shown in Figure 6 shows how these smaller programs feed into the main. These programs all work within each other to find the optimal results for building's chilled water plant.

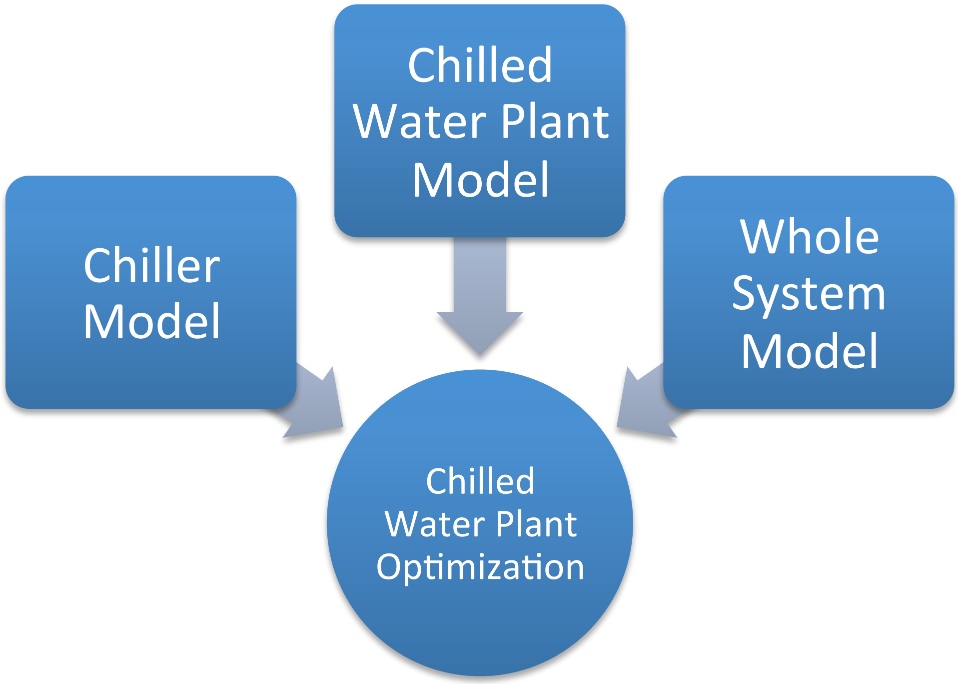

Figure 6. *How the programs link together as one.*

3.3 Chilled Water Plant Model

The chilled water plant model was designed to create a basic model of what calculations are needed to develop a real life system. The final output results were designed to find, the pump, fan, chiller, and total energy consumption for the plant. These output results were based upon the input data of the following: design variables, flow parameters, and given data. With this input data in place, calculations can be made to find the desired outputs.

3.3.1 Design Variables. The design variables, as mentioned earlier, consisted of pipe sizing, chilled water temperature difference, and chilled water supply temperature. When changed, each of these variables can directly affect the energy consumption of the chilled water plant. The uncertainty of what is the proper way to design each of these variables to achieve optimal results was resolved by including conditional parameters that created a range for the input data.

3.3.2 Flow Parameters. The flow parameters of a chilled water plant are designed to ensure a smooth movement of chilled water throughout the plant to cool the air needed for the building. The flow parameters are user inputs in the program that include: pipe roughness, pipe length, K-value for tees/elbows, Cv-value for valves, pressure drop across the chiller, pressure drop across the coil for water side, pressure drop across the coil for air side, design max GPM, design max CFM, design chiller nominal load, and supply air pressure set point. These flow parameters act as unknowns to several equations used to design chilled water plants. In knowing these parameters, a system can be created to test optimal energy saving methods.

Table 3

Flow Parameters (User Inputs)

Variables	Value	Measurement
L	90	length(Ft)
e	0.00015	Pipe roughness for steel (0.00015)
N	10	number of elbow/tees
Dpch	4	pressure accors the chiller (PSI)
Pa	1	Air pressure through AHU (IWG, not include the coil)
Ps	2	Supply air pressure set point (IWG)

3.3.3 Given Data. The given data within this program comes from the information calculated through an energy simulation software. In this study, the energy simulation software eQuest is used. The given data within the program includes: building load, building supply airflow, outdoor dry bulb temperature, and outdoor wet bulb temperature. The eQuest software simulated the hourly results over a calendar year, to gather accurate information for this data.

3.3.4 Calculations. The calculations needed to run the chilled water plant model were broken down into three different steps. The first step was used in finding the GPM needed for the chiller design. This step uses building load as well as the chilled water temperature difference to find the GPM calculation. The second step involved finding several different components that included: head pressure loss, total pressure for water-side, and total pressure for air side. The Darcy-Weisbach Equation is used to find the head pressure loss in the system. In order to find the head pressure loss the velocity of fluid flow, Reynolds Number, and relative roughness of pipe were calculated within the program. Finding the total pressure of the water-side system consisted of calculating three different pressures and adding them together. These different pressures consisted of the following: pipe pressure, pressure with the connections, and the pressure drop across the system. Finding the total pressure of the air-side system consisted of calculating the pressure drop across the system. The third and final step involved calculating the total energy consumption of the system. The total energy consumption is made up of the pump, fan, and chiller energy consumption. The pump and fan energy consumption had calculations built into the chilled water plant model. The chiller energy consumption involved more complex calculations, which led to a chiller model program being created to solve this issue.

3.4 Chiller Model

The chiller model was created to analyze the calculations that are needed to design a chiller. The model is based on the DOE-2 chiller model (Hydeman, 2002; DOE2, 1980) using the default performance curve from the eQUEST library. The objective of this program was to calculate the chiller efficiency, chiller energy consumption, and actual chiller capacity. The input data needed to calculate this information included the following: cooling load, design chiller capacity, chilled water leaving temperature, and condensing chilled water temperature. The calculations found from this program are linked to the chilled water plant model to find the total energy consumption that will be used for the system.

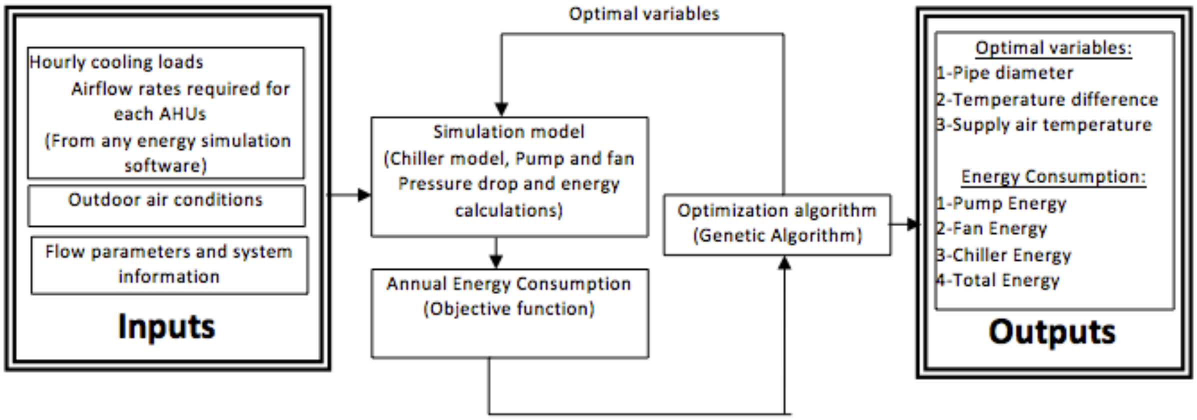

Figure 7. The suggested tool for the optimal design of a chilled water plant.

3.5 Whole System Model

The whole system model served as a method to incorporate the chilled water plant model and chiller model to find energy consumption results for any desired design variables. The whole system model has several imports built into the program that link it to data used to find results for equations. This program works by using the following information: design variables, user inputs, loaded tables, given results from eQuest, design information, flow parameters, and data calculations.

3.5.1 Design Variables. The whole system model program was built to only accept design variables as input values. The design variables will then lead to the program finding desired solutions. This is crucial when trying to find a baseline design of the building in each ASHRAE climate zone.

3.5.2 User Inputs. The user inputs was data that was used to produce calculations for equations through the program. These user inputs include: pipe length, pipe roughness, number of elbows/tees, pressure drop across the chiller, air pressure through the air-handling unit, and supply air pressure set point. The information needed for the pipe come from the design of the system and the flow going through them. The pressure user inputs were calculated through previous equations used in the chilled water plant model.

3.5.3 Loaded Tables. The tables loaded into the whole system model consist of the K-value table, Cv-value table, and pressure table. The K-value table represents the losses in flow due to fittings for piping tees and elbows. The Cv-value table represents the losses in flow due to the fittings for valves in the piping system. The pressure table represents the air and water-side pressure across the coil. These tables are instrumental in finding the needed selections to create efficient system flow.

Table 4

K-Values for steel

Size	Elbows		Tees	
	90°	45°	Straight	Branch
1	0.43	0.22	0.26	1
1.25	0.41	0.22	0.25	0.95
1.5	0.4	0.21	0.23	0.9
2	0.38	0.2	0.2	0.84
2.5	0.35	0.19	0.18	0.79
3	0.34	0.18	0.17	0.76
4	0.31	0.18	0.15	0.7
5	0.3	0.17	0.13	0.66
6	0.29	0.17	0.12	0.62
8	0.27	0.17	0.1	0.58
10	0.25	0.16	0.09	0.53
12	0.24	0.16	0.09	0.5
14	0.23	0.15	0.08	0.5
16	0.23	0.15	0.08	0.47
18	0.22	0.14	0.07	0.44

Table 5

Cv-Values

Size	Cv					
Circuit Setter	Silent Check	Swing Check	Ball	Butterfly	Wye-Strainer	Suction Diffuser
0.5	1.7	6.86	4.8	5	-	26
0.75	2.7	16.3	14.3	12	-	33
1	5.8	30	24	22	-	41
1.25	11	49	43	35	-	50
1.5	20	72	60	52	-	61
2	40	130	102	95	166	72
2.5	62	110	221	-	247	111
3	110	155	327	-	340	164
4	220	278	605	-	660	285
5	420	431	975	-	1080	410
6	650	625	1440	-	1613	597
8	875	1115	2670	-	3759	1000
10	1200	1770	4300	-	5300	1800
12	2250	2500	6350	-	7969	2800
14	-	3400	8600	-	11917	4120
16	-	4400	11400	-	16383	5810
18	-	5600	14700	-	21705	7900
20	-	6900	18100	-	27908	10430
24	-	10000	26800	-	43116	17020
26	-	15400	31000	-	60922	21170
30	-	22400	42000	-	86375	31370

Table 6

Typical coil performance vs. chilled water temperature difference (Taylor, 2011 c)

Chilled Water T (°F),	Coil Water Pressure Drop, (ft of Water),	Coil Airside Pressure Drop (in. of Water)
10	23.5	0.48
13	13.9	0.5
16	9.1	0.52
19	8.3	0.6
22	6.7	0.63
25	4.7	0.78

3.5.4 Given Results From eQuest. The given results from eQuest consist of the building load, supply airflow, outdoor dry bulb temperature, and outdoor wet bulb temperature. The hourly results for a year were imported into program from eQuest. This allows for the data to be analyzed for any specific hour during a calendar year.

3.5.5 Design Information. The chilled water plant is designed using the information found though several calculations. These calculations include: max supply airflow, max building load, and max chilled water flow. The hourly results that were imported from eQuest, make it possible to find the maximum load in a year for each of the needed calculations. In accounting for the maximum load for each, the system can be designed to function under the heaviest load conditions.

3.5.6 Flow Parameters. The flow parameters are all calculated through the whole system model program. The K-value, Cv-value, water-side pressure drop across the coil, and air-side pressure drop across the coil were the last flow parameters to be found. The tables loaded into the whole system model program were used to find a range in which each parameter fell. If the data did not fall directly on the chart, it was interpolated to find accurate results.

3.5.7 Data Calculations. The output data programmed for the whole system model was pump, fan, chiller, and total energy consumption. The chilled water plant model was linked to the whole system model to find these calculations. The flow parameters found through the whole system model, along with the other data found through the chilled water plant and chiller models come together to give an accurate result on the energy consumption of the system.

3.6 Chilled Water Plant Optimization

The chilled water plant optimization program is where all the data from the other programs is gathered to find optimal energy saving results. This program also serves as a bridge between Matlab and Excel. This is a key factor because it allows for data to be imported in the program without the complications that come with different software. The chilled water plant optimization program functions by importing data from Excel, using optimal design variables, running the data through different generations, and exporting the outputs to Excel. This will lead to results that can be analyzed to determine the effectiveness of the program and the changing of the design variables.

3.6.1 Imported Data. An Excel spreadsheet file was incorporated into the program to allow easier access to the data. The tables imported into the whole system model were copied into the Excel spreadsheet. The hourly data from the eQuest energy simulation was also copied into the Excel spreadsheet. With this data imported into the Excel file, the chilled water plant optimization program was able to import the data and interpret the proper information needed to select the correct design data.

Table 7

Imported Data Sample Over A 24-Hour Period

Outside dry-bulb temp (F)	Outside wet-bulb temp (F)	Building Load (Btu/hr)	Supply Air Flow 1 (cfm)	Supply Air Flow 2 (cfm)
62	60	0	0	0
62	60	0	0	0
62	60	0	0	0
62	60	0	0	0
62	60	0	0	0
62	60	0	0	0
62	60	0	0	0
62	61	0	0	0
63	61	121,784	18,811	32,764
65	61	490,426	16,096	27,457
66	60	833,272	15,763	27,223
68	61	954,833	16,855	29,778
70	61	927,932	15,851	29,586
71	62	978,045	15,554	29,341
70	62	1,004,980	16,069	29,249
70	63	1,077,100	16,582	30,744
71	64	1,185,000	16,850	32,535
70	63	1,022,310	15,868	30,313
68	63	726,994	12,915	23,688
68	63	0	0	0
68	63	0	0	0
68	63	0	0	0
68	63	0	0	0
67	64	0	0	0
66	63	0	0	0

3.6.2 Optimal Design Variables. The decision of the what the proper pipe sizing, chilled water temperature difference, and chilled water supply temperature should be was critical to finding the optimal results of the chilled water plant energy consumption. The rule of thumb pipe sizing that would usually be used for this size chilled water plant is about five inches. Knowing this, the parameters or optimal design were set at a range of 1-4 inches. The chilled water temperature difference generally used in practice would be around 10 °F. In order to optimize this variable, the parameters were set between 10-25 °F. The chilled water supply temperature is generally set at 45 °F in standard practice. In order to optimize this variable, the parameters were set between 45-48 °F. With parameters set for the design variables, the optimal energy saving results was expected of the data.

3.6.3 Optimization Algorithm. A genetic algorithm was used to find the most accurate results for the chilled water plant optimization program. Genetic algorithms are typically used within programming software to search for solutions of problems. The generations within the genetic algorithm are used to sort through a multitude of possible solutions. The data was ran through 200 generations before being allowed to export its findings to the Excel spreadsheet.

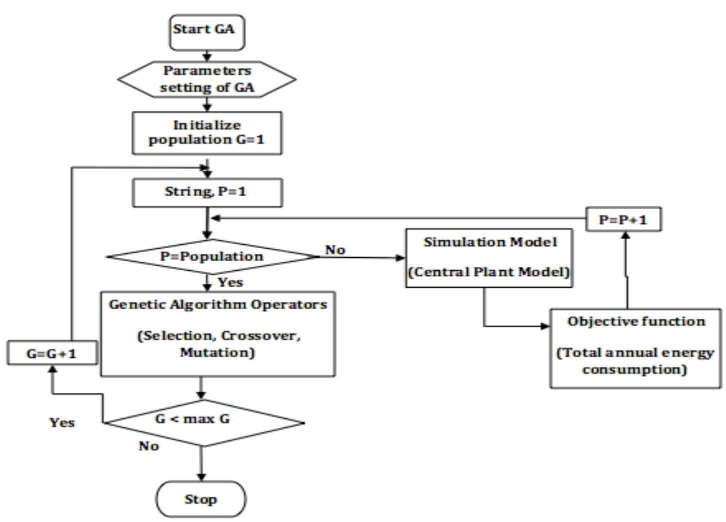

Figure 8. How the genetic algorithm worked for the program.

3.6.4 Outputs in Excel. When the chilled water plant optimization program has finished running the outputs are exported into an Excel spreadsheet file. When the file is opened, two data tables appear with the optimization results. The first table includes the optimal design variables that were calculated for the system. The second table includes the calculated energy consumption results for the chilled water plant.

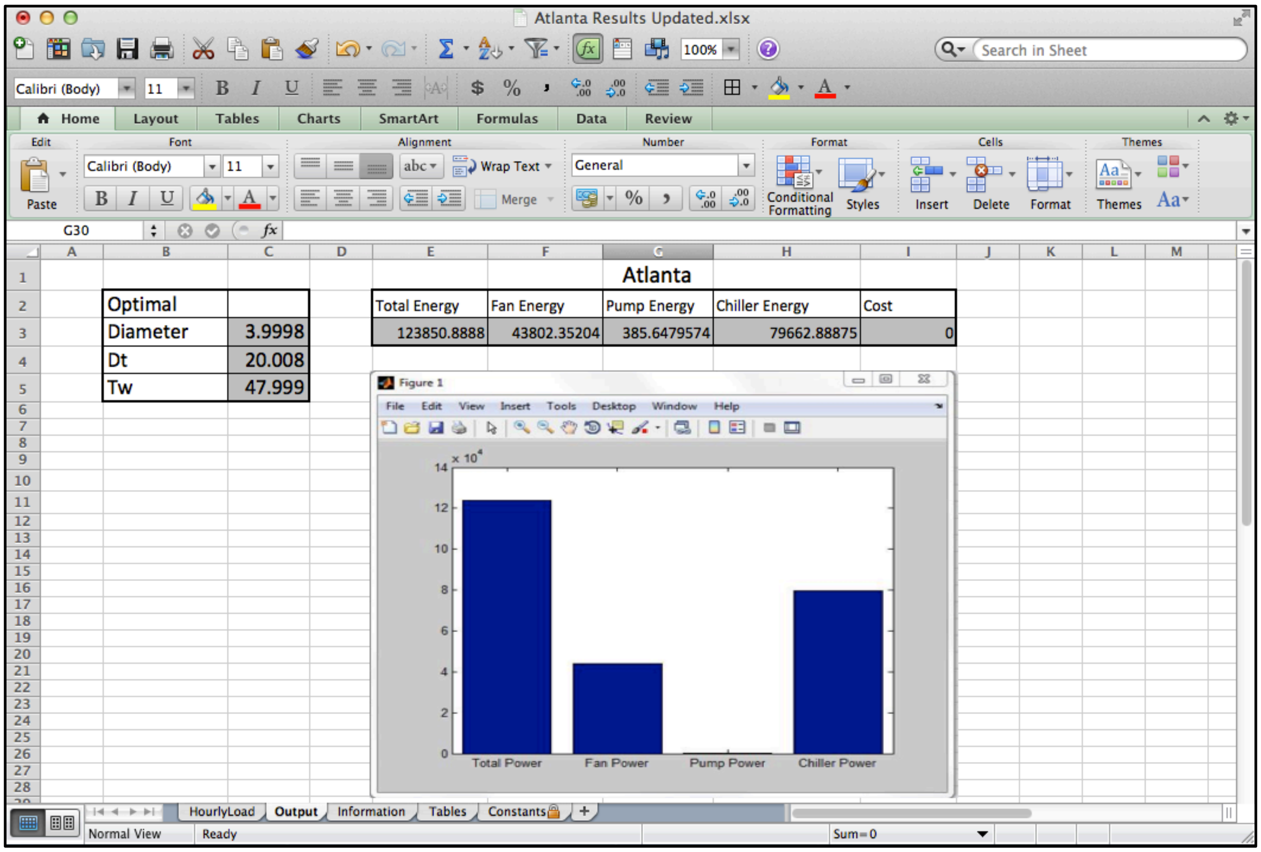

Figure 9. The dual relationship with the optimization program in Excel and Matlab in Atlanta.

3.7 eQuest

In order to analyze the energy consumption used within a building, it must be run through eQuest. An AutoCAD drawing of building's floor plans was created of the building in order to create a digital model of the building. The eQuest program is compatible with AutoCAD, which allowed for the floor plans to be imported straight into eQuest. Once the floor plan is imported into eQuest, the process of placing it in the correct climate zone and selecting the proper energy usage measures our the next step to creating an accurate representation of the building. The eQuest software has a database with numerous locations within the ASHRAE climate zones that can be selected to simulate the building energy consumption within that specific region. The energy usage measures within eQuest focus on the different components and systems within the building, as well as the schedules on which the systems run. These components and systems include: the building envelope, electrical systems, and mechanical systems. Within each of these components lie different parameters you can set according to what is in the actual building; including creating schedule for the daily building occupancy. In the advanced settings of eQuest, there is an option to select specific energy consumption measures to be analyzed. These energy consumption measures include: the building load in BTU/hr, total supply air in cfm, and outdoor dry and wet bulb temperatures in degrees Fahrenheit. When the eQuest building energy simulation is finally run for these measures, the hourly results for everyday of a calendar year in the specified ASHRAE climate zone is measured. This hourly data is needed to get both an accurate and precise results for the energy usage from the building. When the energy simulation concludes, it creates an Excel spreadsheet of the data to be analyzed. Matlab is compatible with Excel so the information from these charts can be imported into Matlab and then into then run through the chilled water optimization program.

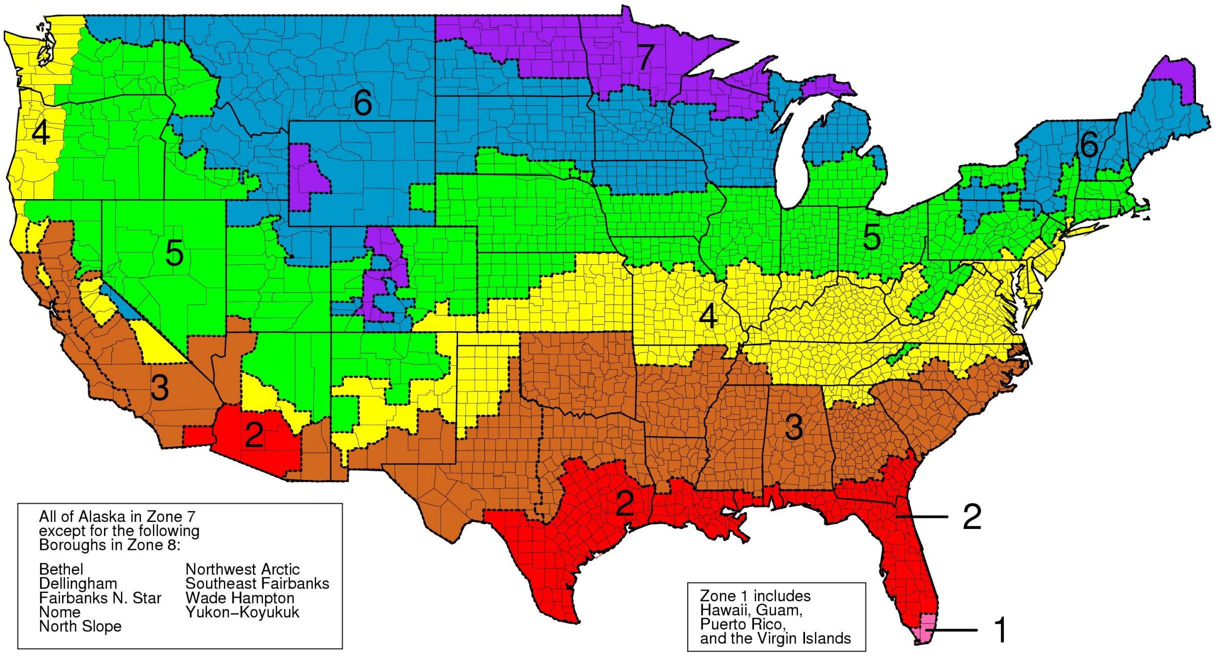

Figure 10. A map of the ASHRAE climate zones (Liu, 2006).

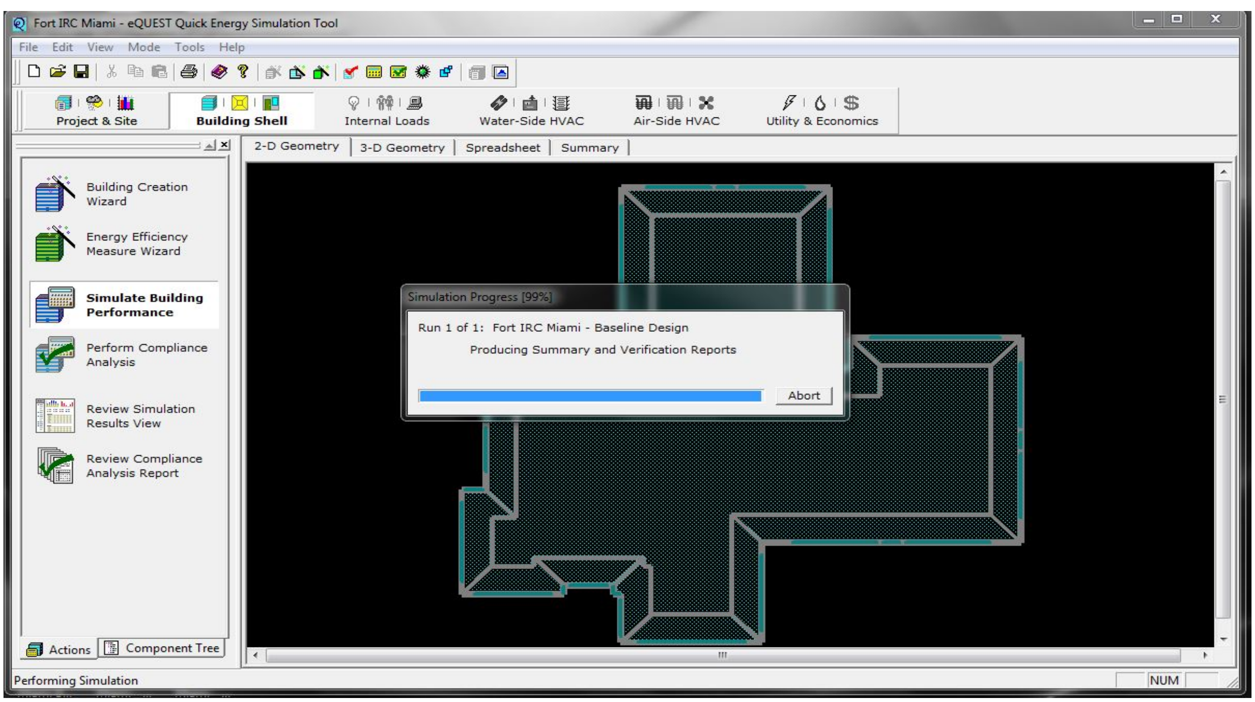

Figure 11. An eQuest energy simulation being run in Miami to get the building load.

3.8 Conceptual Approach

In order to find the optimal design for the chilled water plant, an existing building was taken for analysis. The building's energy consumption was analyzed using the eQuest energy assessment software. An optimization program design in Matlab was written in conjunction with this software in order to find the optimal design pipe sizing, chilled water temperature difference, and chilled water return temperature. The building peak load, total supply CFM, and outdoor dry and wet bulb temperatures of the specific building ASHRAE climate zone collected from the eQuest simulation were used as input data within the Matlab program script that was created. By inserting these input values for the different ASHRAE climate zones, the Matlab program script will determine the optimal designs conditions as well as the pump, fan, chiller, and overall energy consumption. The energy usage results will be based upon the optimized data found by the program. These results will be compared to a baseline design, which uses the rule of thumb non-optimal design conditions to show the energy savings that can be made. All of the data outputs from the chilled water plant optimization program will be displayed in an Excel chart that will determine the optimal design for the plant.

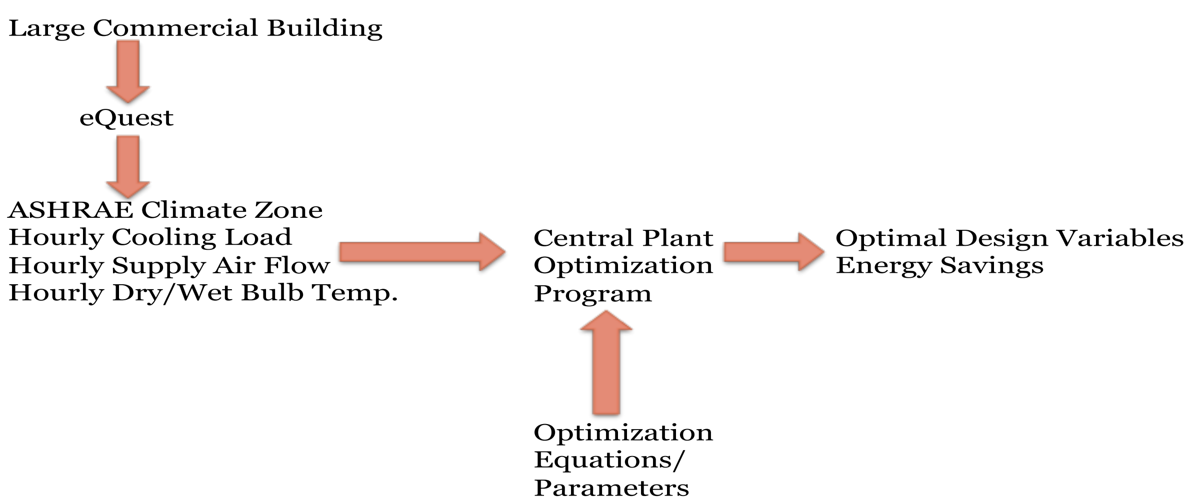

Figure 12. Demonstrates the network of getting the optimization results.

3.9 Data Gathering Methods

The chilled water plant optimization program simulation was conducted in an energy simulation lab. The process of running this program took several hours due to a high population number, which continually tested the yearly data for the chiller plant location in order to achieve accurate results. When the program finished, an optimization output report was generated. From this report the design variable and optimization results were analyzed to determine the usefulness of the data. When the optimization program results were finalized, a non-optimal baseline for the chilled water plant location was taken based on typical rule-of-thumb design variable techniques commonly practiced with pipe sizing, chilled water temperature difference, and chilled water supply temperature. With this data, the percentage of energy saved could be obtained from this data. As a result of all information found, the optimal, non-optimal, and energy saving data was moved into an Excel spreadsheet to be finalized in graph and chart form.

3.10 Validity and Limitations of Data

The validity of the data tested is very strong. The results from the eQuest energy simulation were measured based on a building made to replicate the test building as well as actual design and climate from ASHRAE mandates. This left small room for error when the results were taken and run in the chilled water plant optimization program. The results from the optimization program were based on common load calculations, which are used to find the energy consumption within the components of the buildings. The data from these results supported by calculations, all showed that they followed the expectations that come with changing each design variable. The data within this optimization are still limited by the parameters made within the program, as previously stated. With this limitation, only points that fall within the expected optimization parameters are considered in the program.

3.11 Additional Methods to Operate Program

The method used to operate the program in this research was a combination between the Matlab and Excel. This was an affective approach when testing the usefulness of the program but not when trying to use it in a practical situation. There was two other program operation methods developed in order to account for this drawback. The first of these two methods involved running the program only using Excel by using a compiled application. The compiled application created through Matlab would partner with an Excel spreadsheet file in order for the program to run through Excel shown in Figure 13. The second of the two methods involved compiling the excel file and running it as an application. This process allows the program to run as its own file without the need of Matlab or Excel. The two methods are very practical and would create less of a chance for confusion then operating through two different programs.

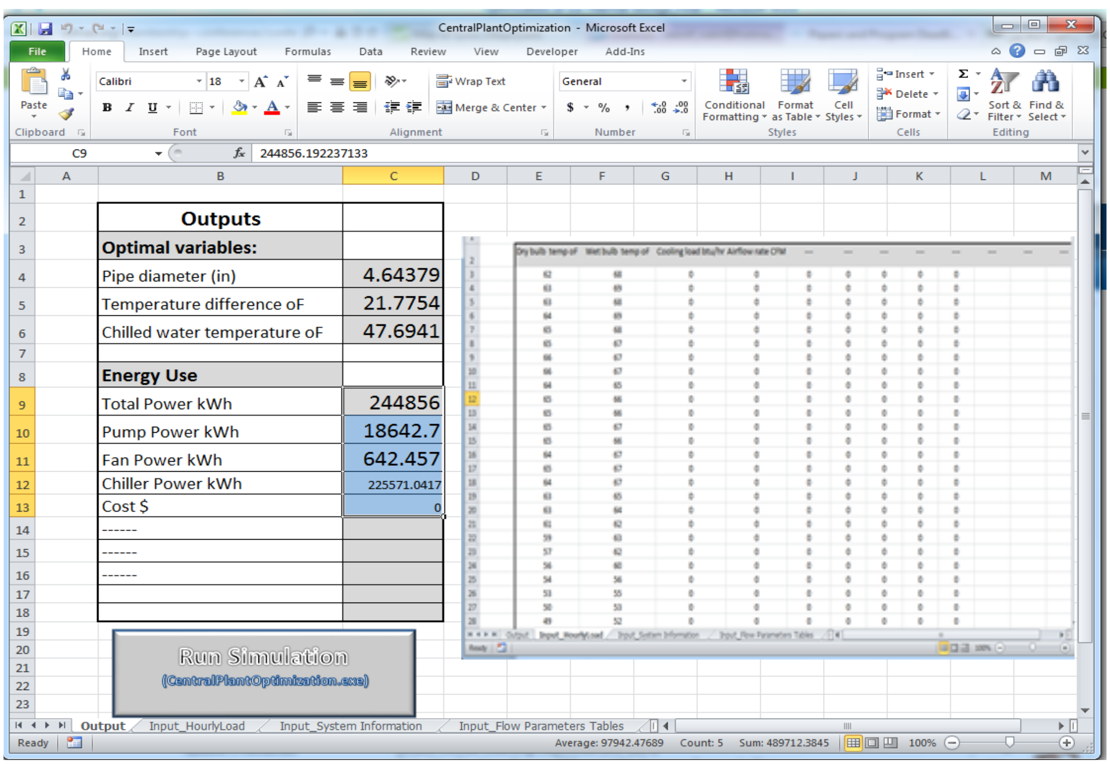

Figure 13. The chilled water plant optimization program being run out of Excel using a compiled application.

CHAPTER 4

Program Analysis

4.1 Introduction

The chilled water optimization program was analyzed using an existing building. The program was run to achieve the optimal design variable results for the chilled water plant. In order to determine if energy was saved, the optimal outputs were compared against non-optimal baseline designs for the building in different climate zones. This comparison included analyzing the energy consumed by the different components of the chilled water plant. This provided a true test of the effectiveness of the program.

4.2 Building Description

The building selected to be tested for this project was the Edward D. Fort Interdisciplinary Research Center Building (IRC), located on the campus of North Carolina Agricultural and Technical State University in Greensboro, NC. The IRC building is four floors, about 77,000 square ft., and serves several different purposes. One of the previous purposes served by this building was acting as the campus library. The IRC building now serves as a home to research laboratories and offices of the Division of Research and Economic Development. The IRC building is also an older construction, which means that many energy conservation measures can be made.

Figure 14. The Edward B. Fort Interdisciplinary Research Center.

4.3 Optimal Results

The chilled water plant optimization program was run for the building in seven ASHRAE climates zones. Table 8 shows the results from the optimization program. The results show a decrease in the pipe sizing from the non-optimal design and show increases in the chilled water temperature difference and chilled water supply temperature for each climate zone. All of the energy consumption measures were reduced in each climate zone with the exception of the fan energy used.

Table 8

Optimization Results

ASHRAE Climate Zone	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Location	Miami	Houston	Atlanta	Greensboro	Chicago	Helena	Duluth
Pipe Sizing (in.)	4	4	4	4	4	4	4
CW Temp Difference (°F)	21	20	20	20	17	13	13
CW Supply Temp (°F)	48	48	48	48	48	48	48
Total Energy Usage (KWH/Yr)	237,839	181,154	123,851	111,372	85,236	65,217	57,463
Fan Energy Usage (KWH/Yr)	50,570	44,377	43,802	41,332	38,233	44,965	39,423
Pump Energy Usage (KWH/Yr)	843	629	386	318	248	201	148
Chiller Energy Usage (KWH/Yr)	186,426	136,148	79,663	69,723	46,754	20,050	17,893

4.4 Non-Optimal Results

The non-optimal results shown in Table 9 were used as a baseline to measure the energy savings found in Table 10. The non-optimal design focused on using the rule of thumb approach typically used in chilled water plant design. The results indicate the energy consumption that can typically expect to be seen in the field today.

Table 9

Non-Optimal Results

ASHRAE Climate Zone	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Location	Miami	Houston	Atlanta	Greensboro	Chicago	Helena	Duluth
Pipe Sizing (in.)	5	5	5	5	5	5	5
CW Temp Difference (°F)	10	10	10	10	10	10	10
CW Supply Temp (°F)	45	45	45	45	45	45	45
Total Energy Usage (KWH/Yr)	249,380	189,800	128,830	115,800	88,233	66,409	58,685
Fan Energy Usage (KWH/Yr)	50,180	44,090	43,540	41,100	38,127	44,962	39,419
Pump Energy Usage (KWH/Yr)	3,110	2,180	1,380	1,140	650	315	217
Chiller Energy Usage (KWH/Yr)	196,090	143,530	83,910	73,560	49,456	21,132	19,049

4.5 Pipe Sizing

The optimal pipe sizing found for each of the climate zones was four inches compared to the five inches for non-optimal design. Figure 15 shows the comparison of the pipe sizing in the different climate zones. Being able to decrease the pipe sizing is crucial for decreasing the initial costs that go into the construction of the chilled water plant.

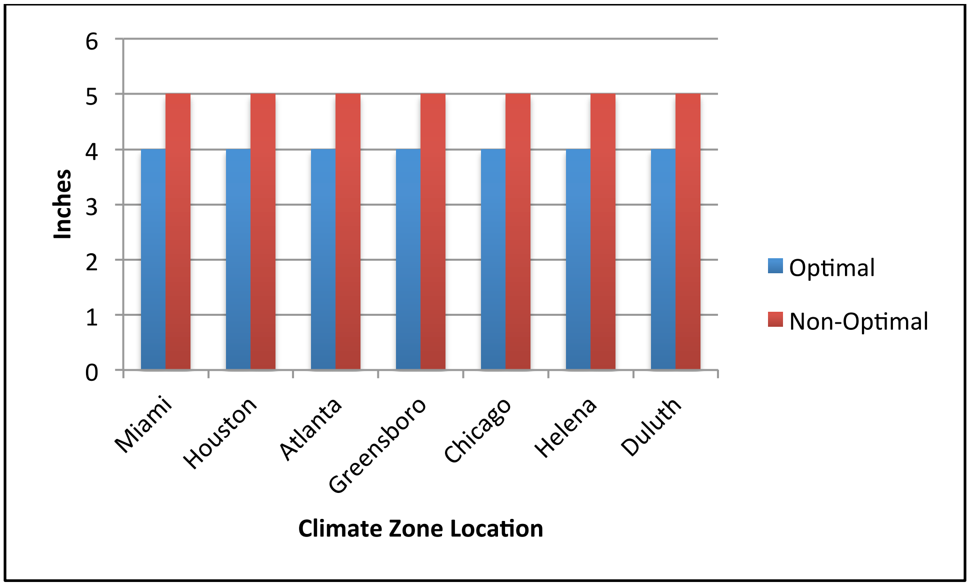

Figure 15. The optimal vs. non-optimal pipe sizing.

4.6 Chilled Water Temperature Difference

The chilled water temperature difference for the optimal design was varied for the different climate zones. This temperature difference ranged from around 17-22 °F with the climates zones in colder regions tending to have lower differences. Figure 16 shows these optimal results compared to a non-optimal rule of thumb measure of 10 °F.

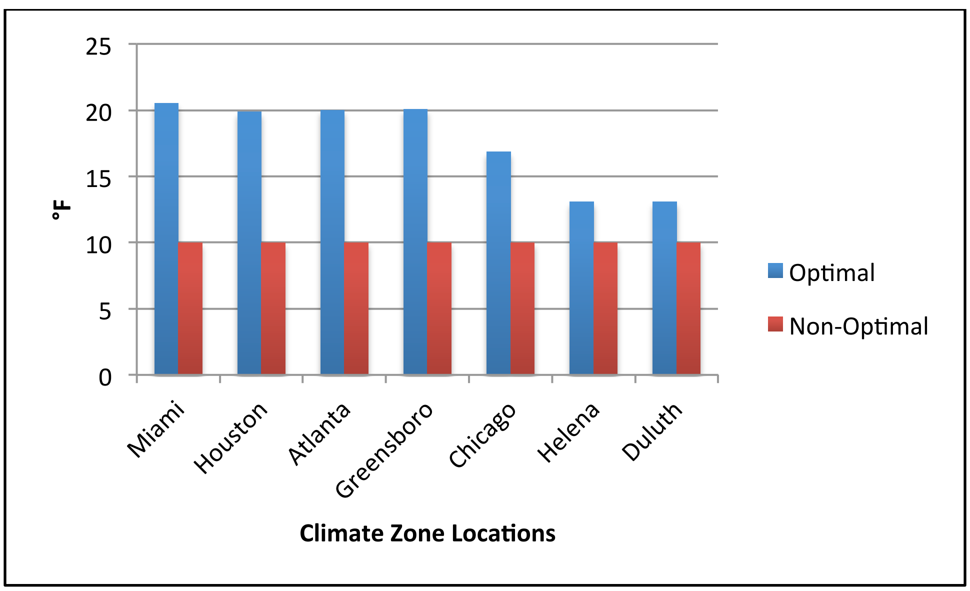

Figure 16. The optimal vs. non-optimal chilled water temperature difference.

4.7 Chilled Water Supply Temperature

The results for optimal chilled water supply temperature stayed consistent at around 48 °F compared to the 45 °F the non-optimal baseline. The data in Figure 17 demonstrates how the vast changes in the temperature through each climate zone had a negligible affect on the chilled water supply temperature.

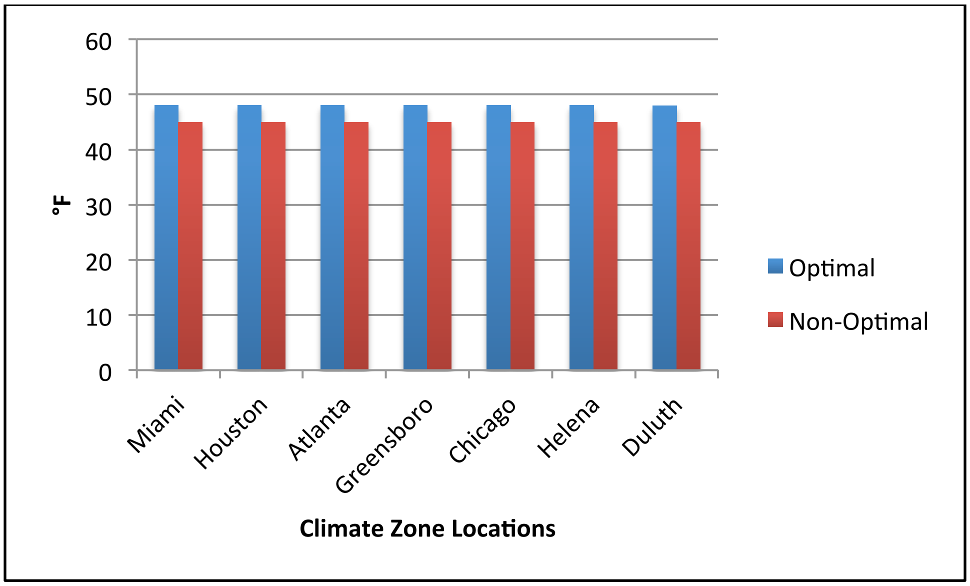

Figure 17. The optimal vs. non-optimal chilled water supply temperature.

4.8 Pump Energy Consumption

The optimal results seen in Figure 18 show a significant drop in amount of energy consumption used in the pump compared to the non-optimal. The energy usage difference between the optimal and non-optimal design is consistent through each of the different climate zones. This difference represents how optimizing the design variables can affect each system in a different way. This is further discussed in the next chapter.

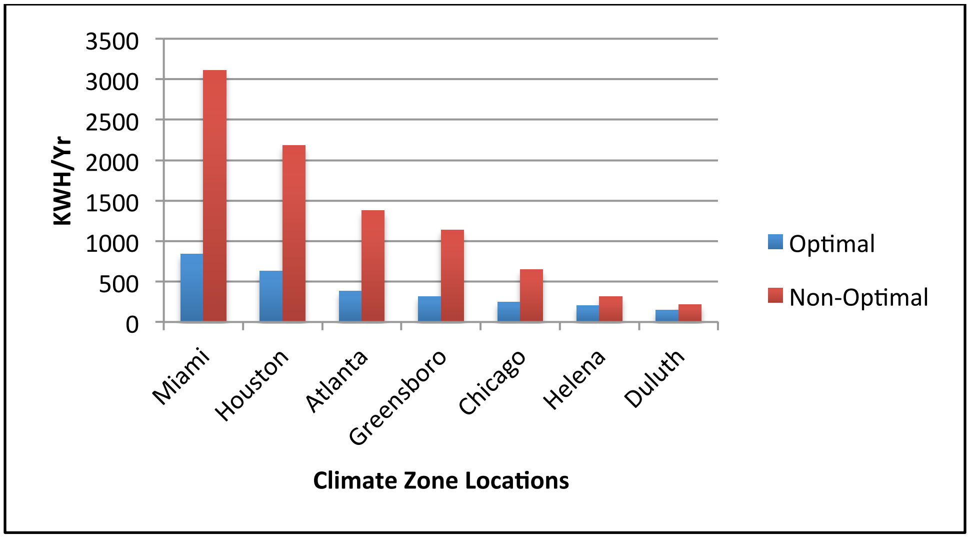

Figure 18. The optimal vs. non-optimal pump energy consumption.

4.9 Fan Energy Consumption

In Figure 19, the optimal energy usage for the fan shows a slight increase compared to the non-optimal results. This pattern is continued through the different climate zones, showing that the change in design variables has affected the fan energy consumption in a negative manner. This increase is expected however due to the relationship each design variable has on the energy consumption of the chilled water plant and is furthered discussed in the next chapter.

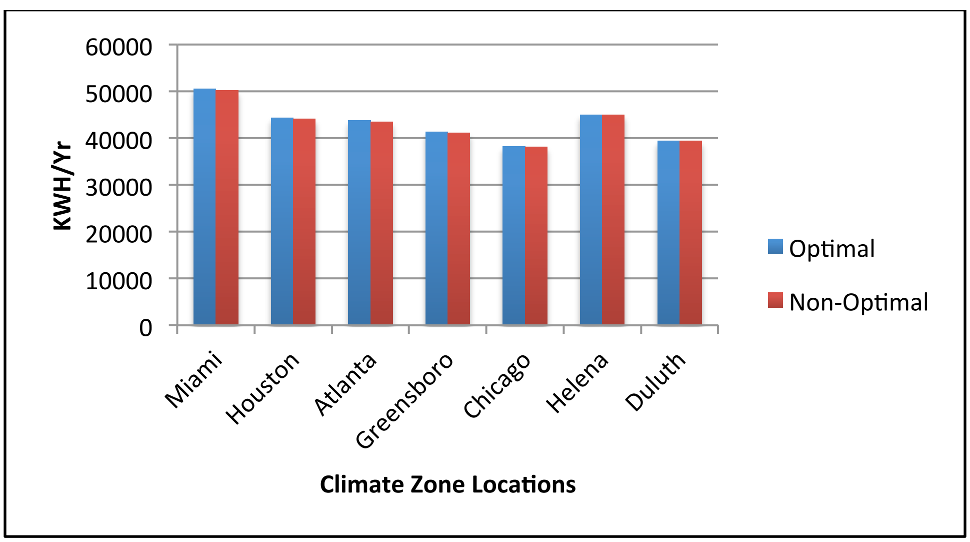

Figure 19. The optimal vs. non-optimal fan energy consumption.

4.10 Chiller Energy Consumption

The energy consumed by the chiller in optimal design, shows a decrease from the non-optimal design. This decrease is shown throughout all of the different climate zones. This demonstrates how the design variables work in the energy usage within the chiller. The reasons behind this decrease our discussed in the next chapter.

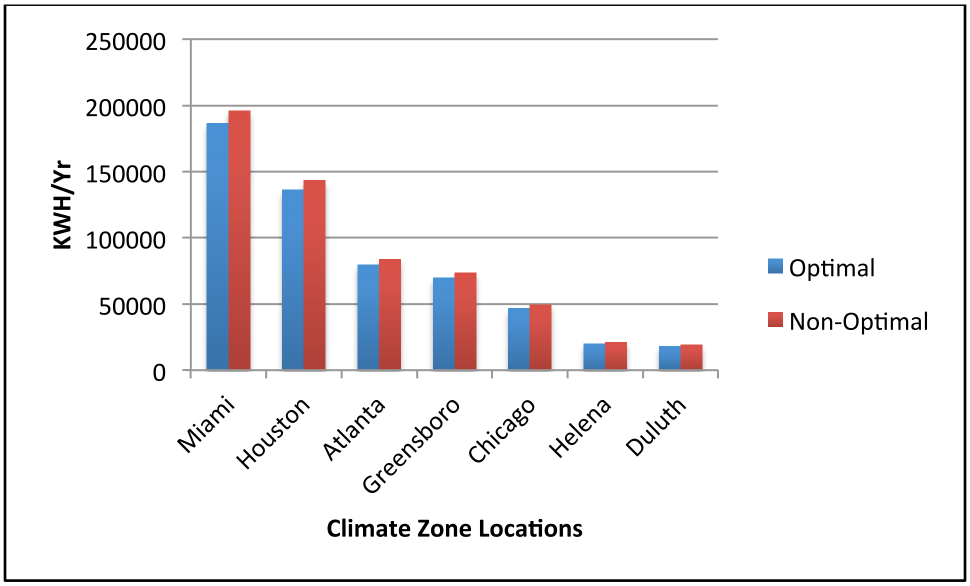

Figure 20. The optimal vs. non-optimal chiller energy consumption.

4.11 Total Energy Consumption

The total energy used by the chilled water plant is shown in Figure 21. The optimal design shows a decrease from the non-optimal design in each of the different climate zones. This overall energy result shows that the optimization program was effective in decreasing the energy usage within a chilled water plant.

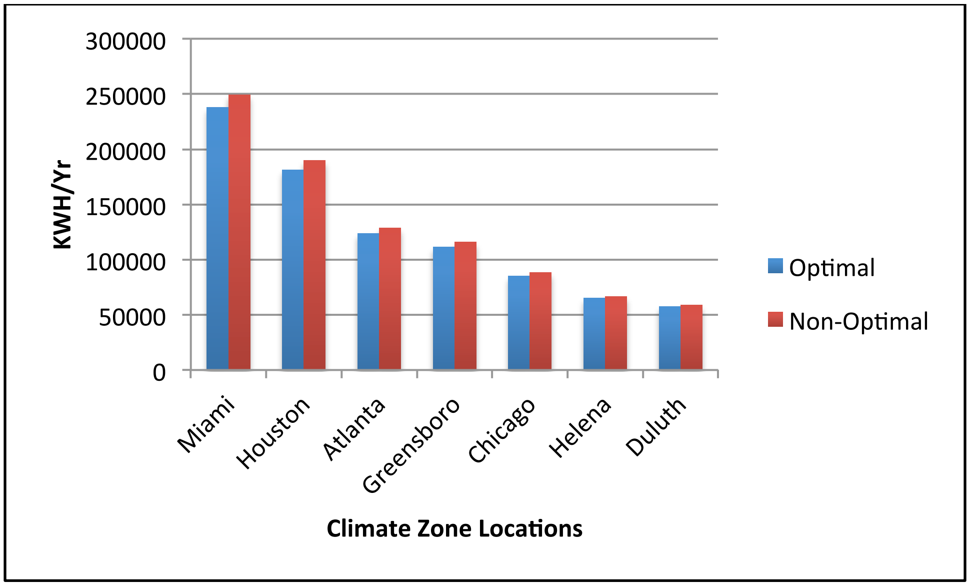

Figure 21. The optimal vs. non-optimal total energy consumption.

4.12 Energy Savings

The energy savings in the chilled water plant were reasonable amount. In Table 8 it can be seen that only the fan energy usage did not save energy. A significant amount of savings in the pump energy usage can be seen as well. These energy savings show that there is a lot of room to change the amount of energy that can be saved when not using optimal design techniques.

Table 10

Energy Savings

ASHRAE Climate Zone	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Location	Miami	Houston	Atlanta	Greensboro	Chicago	Helena	Duluth
Total Energy Usage (%)	4.63	4.56	3.86	3.82	3.40	1.80	2.08
Fan Energy Usage (%)	-0.78	-0.65	-0.60	-0.56	-0.28	-0.01	-0.01
Pump Energy Usage (%)	72.89	71.16	72.05	72.15	61.79	36.16	31.94
Chiller Energy Usage (%)	4.93	5.14	5.06	5.22	5.46	5.12	6.07

CHAPTER 5

Discussion and Future Research

5.1 Introduction

The results from the testing of the chilled water plant optimization program showed that the design variables greatly affect the energy consumed by the system. The energy savings from optimizing these design variables serves as proof that making a change from conventional design will have positive affects of the system. These positive outputs were a great finding but there is still room to push forward with the development of the program. This development will come in the form of testing the design variable parameters to analyze if they can be improved, providing a cost analysis of the chilled water plant within the program, and pursuing add-ins into the current optimization program.

5.2 Design Variables

The allocation of parameters for the design variables in the chilled water plant optimization program allowed for a variety of possible results for the input data. This variety of results makes for an optimization program that can affectively decipher the correct combination of design variable measurements. In examining the design variable of pipe sizing, it was determined that a five-inch pipe size would be a typical rule of thumb design needed by the IRC building based on Table 9. In order to optimize upon this design, the only option was to set pipe size parameters less then five inches. The outputs from the all seven of the ASHRAE climate zones determined that a four-inch pipe sizing would be optimal when compared with the other design variables. In a continued examination of the design variables, the chilled water temperature difference was found to be most efficient from 10-25°F. The low end of this range was considered as the non-optimal result that would typically be used. The high end of the range was considered to be an optimal design for the system to reach. The outputs from the optimization program supported this theory with the majority of the climate zone locations being closer to the higher end the temperature difference range. A pattern in the chilled water temperature difference as the climate zones move into colder regions does show a downward trend. This trend is logical because as the climate locations get colder, less load is demanded from the chilled water plant. The last design variable that was examined was the chilled water supply temperature. This temperature directly affects the chiller energy consumption due to the chiller trying to cool down return water to this desired set point. This temperature cannot be too low because of this very same correlation and cannot be too high because of humidity problem within the system. With this in mind, the parameters of the chilled water supply temperature were set at 42°F at the low end and 48°F at the high end. Knowing that a higher supply temperature equated to less energy consumption, it was to no surprise that the chilled water temperature difference for each of the climate zones were approximately 48°F. With the newly optimized design variables, there was a common trend between both the pipe sizing and chilled water supply temperatures of the different climate zones. The two design variables both reached the max of the parameters set however the chilled water temperature difference varied between them all. This indicates that finding optimal pipe sizing and chilled water supply temperatures results affect the chilled water plant energy consumption directly, while the chilled water temperature differences are more dependent on the climate zone location and affect it indirectly.

Table 11

Piping System Design Maximum Flow Rate in GPM (Taylor, 2011 c)

Operating Hours/Year	≤2,000 Hours/Year		>2,000 and ≤4,400 Hours/Year		>4,400 and ≤8,760	
Nominal Pipe Size (in.)	Other	Variable Flow/ Variable Speed	Other	Variable Flow/ Variable Speed	Other	Variable Flow/ Variable Speed
2.5	120	180	85	130	68	110
3	180	270	140	210	110	170
4	350	530	260	400	210	320
5	410	620	310	470	250	370
6	740	1,100	570	860	440	680
8	1,200	1,800	900	1,400	700	1,100
10	1,800	2,700	1,300	2,000	1,000	1,600
12	2,500	3,800	1,900	2,900	1,500	2,300
Maximum Velocity for Pipes Over 12in. Size	8.5 fps	13.0 fps	6.5 fps	9.5 fps	5.0 fps	7.5 fps

5.3 Energy Savings

The chilled water plant optimization program produced results that showed improving the design variables for a chilled water plant was an effective way to reduce its energy consumption. The most evident energy savings were seen in the pumps. There was a huge drop in the energy consumption of the optimal design compared against the non-optimal design for the pump in each of the climate zone. This drop in pump energy usage needed is a product of the inversely proportional relationship between the pipe sizing and chilled water temperature design variables. The higher the chilled water temperature difference the smaller the pipe sizing that is required. Smaller pipe sizes combined with lower flow rates result in less pump energy usage needed to push the chilled water through the piping network. The increased chilled water temperature difference also approaches or exceeds the pressure drop limit across the coil of the chilled water plant. In order to solve this issue, rows must be added to the coil that requires the air velocity across them to be increased. This explains the optimization outputs having an increase in fan energy consumption when compared to the non-optimal results. The chiller energy consumption is more dependent on the chilled water supply temperature rather then the other two design variables. The increase of the chilled water supply temperature in optimal design allowed for a decrease in energy usage. In all, there was notable total energy savings seen in all of the climate zones showing that chilled water plant optimization can play an important role in decreasing energy consumptions and costs.

5.4 Changing Optimal Design Variables

The optimal design variables for the chilled water plant are unknown measures. The closest way of finding these unknown measures is by creating parameters for them that each may fall. In Table 12, two of parameters of the chilled water plant optimization program for one climate zone were changed to observe the difference in energy savings compared to the current program. The design variable parameter changes were that of the pipe sizing and chilled water supply temperature. In one of the tests, two of the design variable parameters were left the same and the pipe sizing parameters were set from 1-10 inches in comparison to 1-4 inches for the original optimization program. This resulted in the optimal pipe sizing being determined as eight inches and led to the chilled water temperature difference decreasing. The energy savings shown in Table 13 for the change in pipe sizing reveal that the energy savings actually decreased with a larger pipe size. This option has another negative affect when the installation of larger pipes is considered. The second of the two tests, two of the design variables were left the same and the chilled water supply temperature parameters were set from 42-50°F in comparison to 42-48°F for the original optimization program. This resulted in the optimal chilled water supply temperature being 49°F and the chilled water temperature difference increasing. The energy savings shown in Table 13 for the change in chilled water supply temperature reveal that an increase in energy savings with an increase in supply temperature. This shows that an increase of the parameter limits for the chilled water temperature should be considered when running the optimization program. The one concern with this raise in supply temperature is dealing a humid climate zone that will not allow for too high of a supply temperature because of humidity problems within the system. This issue may be written into the program code to be adjusted according to climate zones creating a more efficient optimization program.

Table 12

Change in Pipe Size and Chilled Water Supply Temperature

Design Parameter Changes	Pipe Size	CW Supply Temp.
Location	Atlanta	Atlanta
Pipe Sizing (in.)	8	4
CW Temp Difference (°F)	17	21
CW Supply Temp (°F)	48	49
Total Energy Usage (KWH/Yr)	123,932	122,962
Fan Energy Usage (KWH/Yr)	43,706	43,807
Pump Energy Usage (KWH/Yr)	363	363
Chiller Energy Usage (KWH/Yr)	79,863	78,791

Table 13

Energy Savings

Design Parameter Changes	Pipe Size	CW Supply Temp.
Location	Atlanta	Atlanta
Total Energy Usage (%)	3.80	4.55
Fan Energy Usage (%)	-0.38	-0.61
Pump Energy Usage (%)	73.70	73.70
Chiller Energy Usage (%)	4.82	6.10

5.5 Cost Analysis

The demand for energy savings is critical to reach the demand for cost savings when dealing with chilled water plant. The cost to operate the system is a massive problem and many different efforts are being exerted to reduce these costly measures. When designing the chilled water plant it is important to remember both installation and operation costs should be examined. The return on investment of installing the system should be met with operation cost savings during the lifetime of the chilled water plant. The future chilled water optimization program will need to incorporate all of these costs in the future to become an even more informative program.

The importing of Excel spreadsheet files of common installation and labor costs into the optimization program will act as a vital add-in feature. The energy savings from the output data will be taken and exported into an Excel chart that shows the cost savings per year and a return on investment date. This will affectively create a newer program that is more beneficial to real life applications.

5.6 Optimization of Other Systems

The chilled water optimization program has room to expand and find optimal design results for other systems that serve large commercial businesses. Future enhancements to the program include but are not limited to finding the optimal design for the following: hot water plant, condenser water loop, potential ice storage chiller system, and water source heat pumps. The implementation of the hot water plant, condenser water loop, and water source heat pump upgrades will follow in the program design of the chilled water plant. Each of these upgrades will be broken down into smaller programs that solve small issues within their respective programs and link together into a bigger program that optimizes the whole system. The ice storage chiller system would be written as a design option into the chilled water plant optimization program. These future upgrades to the chilled water plant optimization program will allow it to be more universally used and recognized as a top optimization program.

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Appendix A

CentralPlantModel.m

This file can be published to a formatted document. For more information, see the publishing video or help.

```matlab
function [TotalPower,FanPower,PumpPower,ChillerPower,Cost]=CentralPlantModel(Inputs,FlowParameters, Given)
%CentralPlantModel([8,10,45],[0.0001,50,0.1,0.1,5,10,2,250,40000,40000,100], [1000000,20000,20000,85,75])
%Inputs are (1) pipe diameter d in, (2) temperature difference Dt oF, (3)
%chilled water temeprature oF
%
%%Inputs
d=Inputs(1);
Dt=Inputs(2);
Tw=Inputs(3);
%%
%Flow Parameters inclduing design water and airflow rates GPM and CFM and q
e=FlowParameters(1);%Pipe Roughness e it is 0.00015 for Steel
L=FlowParameters(2);%pipe lenght ft
K=FlowParameters(3); %K-value for tees/elbows
Cv=FlowParameters(4); %Cv-value for valves
DPch=FlowParameters(5); %for chiller
DPw=FlowParameters(6); %for the coil water side
DPa=FlowParameters(7); %for the coil air side plus other parts
GPMmax=FlowParameters(8);%design GPM
CFM1max=FlowParameters(9);%design CFM1
CFM2max=FlowParameters(10);%design CFM2
qomax=FlowParameters(11);%design chiller nominal load
Ps=FlowParameters(12);%In water gage
%%
%Given. data are collected annualy from eQuest (qo, CFM1, CFM2, to,twb)
q0=Given(1);
CFM1=Given(2);
CFM2=Given(3);
to=Given(4);
twb=Given(5);
%%
% STEP 1
GPM=q0/(500*Dt);
% Add if GPM<min(GPM)
%%
%STEP 2
Velocity1=(GPM*0.1337)/(pi*(d/12)^2/4); %fpm
Velocity=Velocity1/196.9; %m/s
Re=62.4*Velocity1/60*(d/12)/(9.4*10^-4);
E=e/(d*12); % Relative roughness
fun=@(f)1/sqrt(f)+2*log10(e/(3.7*d)+2.5/(Re*sqrt(f)));
options=optimset('Display','off');
if Velocity1>10
    f1=fsolve(fun,0.01,options);
```

Figure A 1. Programming script for the Chilled Water Plant Model.

```
    else
        f1=0;
    end
    PSI1=f1*(L/(d/12))*62.4*(Velocity1/60)^2/(2*32.14)/144;% for pipe
    PSI2=(K+Cv)*62.4*(Velocity1/60)^2/(2*32.14)/144;% for connections
    PSI3=DPch*(GPM/GPMmax)^2+DPw*(GPM/GPMmax)^2;
    PSI=PSI1+PSI2+PSI3;
    % AIR Side
    IWG1=DPa*(CFM1/CFM1max)^2+Ps;
    IWG2=DPa*(CFM2/CFM2max)^2+Ps;

    %%
    %STEP 3 Chiller power
    [e,ChillerPower,Q_available]=ChillerModel(q0,qomax/12000,Tw,twb+5);
    %Fan and Pump Power
    HP_p=GPM*PSI/(1713*0.8);
    PumpPower=HP_p*0.75;
    HP_f=CFM1*IWG1/(6357*0.8)+CFM2*IWG2/(6357*0.8);
    FanPower=HP_f*0.75;
    TotalPower=ChillerPower+PumpPower+FanPower;
    Cost=0;
```

Figure A 2. Programming script for the Chilled Water Plant Model continued.

ChillerModel.m

```
function [e,Power,Q_available]=ChillerModel(qc,Q_nominal,Twchl,Twl_con)
%qc: cooling load (Btu/hr)
%Q_nominal: design chiller capacitiy (rating capacity) [ton]
%Twchl: chilled water leaving temperature oF
%Twl_cond: condesing chilled water temperature is approximation eqaul to wetbulb+8oF (for Water-Cooled chiller)
%Q_available: chilled capacitiy available under current conditions [ton]
%Power: Chiller power [kW]
%e efficiency (Or COP)
CAP_FT=0.89823067+0.00045350*Twchl+0.00023690*Twchl*Twchl-0.00104750*Twl_con-0.00002930*Twl_con*Twl_con-0.00002035*Twl_con*Twchl;
EIR_FT= 0.62493622-0.00099309*Twchl+0.00017366*Twchl*Twchl-0.00086447*Twl_con+0.00019627*Twl_con*Twl_con -0.00033770*Twl_con*Twchl;

Q_available=CAP_FT*Q_nominal;%[ton] actual cooling capacity
PLRc=qc/(Q_available*12000);
P_nominal=Q_nominal* 0.6;

Dt=Twl_con-Twchl;
if Dt<0
    Dt=0;
end
EIR_FPLR=-0.11699212+1.26354504*PLRc-0.21946673*PLRc*PLRc+0.00294536*Dt+0.00001688*Dt^2-0.00185917*Dt*PLRc;
Pref=P_nominal*EIR_FPLR*EIR_FT*CAP_FT;
Power=Pref;
if qc<=0
    Power=0;
end
if Q_available<0
    Q_available=0;
end
if Power<0
    Power=0;
end
e=qc/12000/Power*3.51;
```

Figure A 3. Programming script for the Chiller Model.

MainModelAll.m

This file can be published to a formatted document. For more information, see the publishing video or help.

```
function Outputs=MainModelAll(Inputs)
%% Inputs or problem variables
d=Inputs(1);
Dt=Inputs(2);
Tw=Inputs(3);

%% Given Information Read from excel sheet
%User Input
load Informationdata.mat
L=Informationdata(1); % L pipe lenght ft
e=Informationdata(2); %Pipe Roughness e it is 0.00015 for Steel
N=Informationdata(3); %number of elbows/tees
DPch=Informationdata(4); %pressure drop across the chiller
Pa=Informationdata(5);    %air pressure thorugh Air handler unit not include the coil
Ps=Informationdata(6);    % supply air pressure set point

%Load Tables
load kTable.mat %K-value for tees/elbows N number of elbows/tees
load CvTable.mat %Cv-value for valves
load PressureTable.mat % to find air and water side pressure across coil as a function of Dt
                     %DPw for water side, DPa for air side

% Given from eQuest
load Hourlydata Hourlydata
q=Hourlydata(:,3);Given(:,1)=q;
CFM1=Hourlydata(:,4);Given(:,2)=CFM1;
CFM2=Hourlydata(:,5);Given(:,3)=CFM2;
to=Hourlydata(:,1);Given(:,4)=to;
twb=Hourlydata(:,2);Given(:,5)=twb;

%Design information (Calculated from eQuest)
CFM1max=max(CFM1)*1.0;%design CFM1
CFM2max=max(CFM2)*1.0;%design CFM2
qomax=max(q)*1.0;%design chiller nominal load
GPMmax=qomax/500/Dt;

%% FlowParameters
%Table look up
K=interp1(kTable(:,1),kTable(:,2),d,[],'extrap');
Cv=interp1(CvTable(:,1),CvTable(:,3),d,[],'extrap'); Cv=0.5;
CorrectionTw=Tw-43;
DPw=interp1(PressureTable(:,1),PressureTable(:,2),Dt-0,[],'extrap');
DPa=interp1(PressureTable(:,1),PressureTable(:,3),Dt-CorrectionTw,[],'extrap');
```

Figure A 4. Programming script for the Whole System Model.

```
FlowParameters(1)=e;
FlowParameters(2)=L;
FlowParameters(3)=N*K;
FlowParameters(4)=Cv;
FlowParameters(5)=DPch;
FlowParameters(6)=DPw*0.4335;
FlowParameters(7)=DPa+Pa; %for the coil air side plus other parts not including the "Ps" set point
FlowParameters(8)=GPMmax;
FlowParameters(9)=CFM1max;
FlowParameters(10)=CFM2max;
FlowParameters(11)=qomax;
FlowParameters(12)=Ps;
%% Calcuation
for i=1:size(Given,1)
    [TotalPower(i),FanPower(i),PumpPower(i),ChillerPower(i),Cost(i)]=CentralPlantModel(Inputs,FlowParameters, Given(i,:));
    Output=[TotalPower,FanPower,PumpPower,ChillerPower,Cost];
end
Outputs=sum([TotalPower',FanPower',PumpPower',ChillerPower',Cost']);
```

Figure A 5. Programming script for the Whole System Model continued.

CentralPlantOptimization.m

This file can be published to a formatted document. For more information, see the publishing video or help.

```
function CentralPlantOptimization()
%% Import the data
%Import Hourly load and Outdoor air conditions
[~, ~, raw] = xlsread('CentralPlantOptimization.xlsx','HourlyLoad','B3:F9000');
data = reshape([raw{:}],size(raw));
data(any(isnan(data),2),:)=[];
Hourlydata=data;
save Hourlydata Hourlydata
%Import Given Information and Flow Paramters
[~, ~, raw] = xlsread('CentralPlantOptimization.xlsx','Information','C4:C9');
data1 = reshape([raw{:}],size(raw));
data1(any(isnan(data1),2),:)=[];
Informationdata=data1;
save Informationdata Informationdata

%Import Given Tables
[~, ~, raw] = xlsread('CentralPlantOptimization.xlsx','Tables','B5:F19');
data2 = reshape([raw{:}],size(raw));
data2(any(isnan(data2),2),:)=[];
kTable=data2;
save kTable kTable

%Import Given Tables
[~, ~, raw] = xlsread('CentralPlantOptimization.xlsx','Tables','H4:O24');
data2 = reshape([raw{:}],size(raw));
data2(any(isnan(data2),2),:)=[];
CvTable=data2;
save CvTable CvTable

%Import Given Tables
[~, ~, raw] = xlsread('CentralPlantOptimization.xlsx','Tables','Q4:S9');
data2 = reshape([raw{:}],size(raw));
data2(any(isnan(data2),2),:)=[];
PressureTable=data2;
save PressureTable PressureTable

%%
var=3;
%%----------Generation G=10
options = gaoptimset('Generations',10,'PopulationSize',10);
[x,fval1,exitflag,output,population]=ga(@MainModel,var,[],[],[],[],[1 10 42]',[4 25 48]',[],options);
Outputs=MainModelAll(x);
xlswrite('CentralPlantOptimization.xlsx',x','Output','C3:C5');
xlswrite('CentralPlantOptimization.xlsx',Outputs,'Output','E3:I3');
```

Figure A 6. Programming script for the Chilled Water Plant Optimization.

```
dat = [x,Outputs];
cnames = {'Diameter','Delta t','Chilled water','Total Power','PumpPower','Fan Power','ChillerPower','Cost'};
rnames = {'G=10','G=50','G=100','G=200'};
figure(1)
t = uitable('Data',dat,'ColumnName',cnames,...
            'RowName',rnames,'Position',[300 300 900 200],'FontSize',12);
set(t,'ColumnWidth',{100})
uicontrol('Style','edit','String','Outputs','Position',[300 500 100 50],'FontSize',14);
uicontrol('Style','edit','String','Developed by Dr.Nabil Nassif','Position',[300 600 300 50],'FontSize',14);

hp=uicontrol('style','togglebutton');
set(hp,'position',[1 1 120 20]);
set(hp,'string','Go to next G=50')
set(hp,'callback',@callbackfnG50)
%%
%%----------Generation G=50
function callbackfnG50(source, eventdata)
options = gaoptimset('Generations',40,'PopulationSize',10);
options = gaoptimset('InitialPopulation',population);
[x,fval2,exitflag,output,population]=ga(@MainModel,var,[],[],[],[],[1 10 42]',[4 25 48]',[],options);
Outputs=MainModelAll(x);
xlswrite('CentralPlantOptimization.xlsx',x','Output','C3:C5');
xlswrite('CentralPlantOptimization.xlsx',Outputs,'Output','E3:I3');
a=get(t,'data');
dat1 = [x,Outputs];
dat=[a;dat1];
figure(1)
t=uitable('Data',dat,'ColumnName',cnames,...
            'RowName',rnames,'Position',[300 300 900 200],'FontSize',12);
set(t,'ColumnWidth',{100})
set(hp,'string','Go to next G=100')
set(hp,'callback',@callbackfnG100)
%%
%----------Generation G=100
function callbackfnG100(source, eventdata)
options = gaoptimset('Generations',50,'PopulationSize',10);
options = gaoptimset('InitialPopulation',population);
[x,fval3,exitflag,output,population]=ga(@MainModel,var,[],[],[],[],[1 10 42]',[4 25 48]',[],options);
Outputs=MainModelAll(x);
xlswrite('CentralPlantOptimization.xlsx',x','Output','C3:C5');
xlswrite('CentralPlantOptimization.xlsx',Outputs,'Output','E3:I3');
a=get(t,'data');
```

Figure A 7. Programming script for the Chilled Water Plant Optimization continued.

```
dat1 = [x,Outputs];
dat=[a;dat1];
figure(1)
t=uitable('Data',dat,'ColumnName',cnames,...
            'RowName',rnames,'Position',[300 300 900 200],'FontSize',12);
set(t,'ColumnWidth',{100})
set(hp,'string','Go to next G=200')
set(hp,'callback',@callbackfnG200)
%%
function callbackfnG200(source, eventdata)
%----------Generation G=200
options = gaoptimset('Generations',100,'PopulationSize',10);
options = gaoptimset('InitialPopulation',population);
[x,fval4,exitflag,output,population]=ga(@MainModel,var,[],[],[],[],[1 10 42]',[4 25 48]',[],options);
Outputs=MainModelAll(x);
xlswrite('CentralPlantOptimization.xlsx',x','Output','C3:C5');
xlswrite('CentralPlantOptimization.xlsx',Outputs,'Output','E3:I3');
a=get(t,'data');
dat1 = [x,Outputs];
dat=[a;dat1];
figure(1)
uitable('Data',dat,'ColumnName',cnames,...
            'RowName',rnames,'Position',[300 300 900 200],'FontSize',12);
set(t,'ColumnWidth',{100})
%% Write to xls
xlswrite('CentralPlantOptimization.xlsx',x','Output','C3:C5');
xlswrite('CentralPlantOptimization.xlsx',Outputs,'Output','E3:I3');
end
end
end
end
```

Figure A 9. Programming script for the Chilled Water Plant Optimization continued.

Appendix B

Table B 1

K-value

Size	Elbows		Tees	
	90°	45°	Straight	Branch
1	0.43	0.22	0.26	1
1.25	0.41	0.22	0.25	0.95
1.5	0.4	0.21	0.23	0.9
2	0.38	0.2	0.2	0.84
2.5	0.35	0.19	0.18	0.79
3	0.34	0.18	0.17	0.76
4	0.31	0.18	0.15	0.7
5	0.3	0.17	0.13	0.66
6	0.29	0.17	0.12	0.62
8	0.27	0.17	0.1	0.58
10	0.25	0.16	0.09	0.53
12	0.24	0.16	0.09	0.5
14	0.23	0.15	0.08	0.5
16	0.23	0.15	0.08	0.47
18	0.22	0.14	0.07	0.44

Table B 2

Cv-values for steel

Size	Cv					
Circuit Setter	Silent Check	Swing Check	Ball	Butterfly	Wye-Strainer	Suction Diffuser
0.5	1.7	6.86	4.8	5	-	26
0.75	2.7	16.3	14.3	12	-	33
1	5.8	30	24	22	-	41
1.25	11	49	43	35	-	50
1.5	20	72	60	52	-	61
2	40	130	102	95	166	72
2.5	62	110	221	-	247	111
3	110	155	327	-	340	164
4	220	278	605	-	660	285
5	420	431	975	-	1080	410
6	650	625	1440	-	1613	597
8	875	1115	2670	-	3759	1000
10	1200	1770	4300	-	5300	1800
12	2250	2500	6350	-	7969	2800
14	-	3400	8600	-	11917	4120
16	-	4400	11400	-	16383	5810
18	-	5600	14700	-	21705	7900
20	-	6900	18100	-	27908	10430
24	-	10000	26800	-	43116	17020
26	-	15400	31000	-	60922	21170
30	-	22400	42000	-	86375	31370

Table B 3

Typical coil performance vs. chilled water temperature difference (Taylor 2011a)

Chilled Water T (°F),	Coil Water Pressure Drop, (ft of Water),	Coil Airside Pressure Drop (in. of Water)
10	23.5	0.48
13	13.9	0.5
16	9.1	0.52
19	8.3	0.6
22	6.7	0.63
25	4.7	0.78

Appendix C

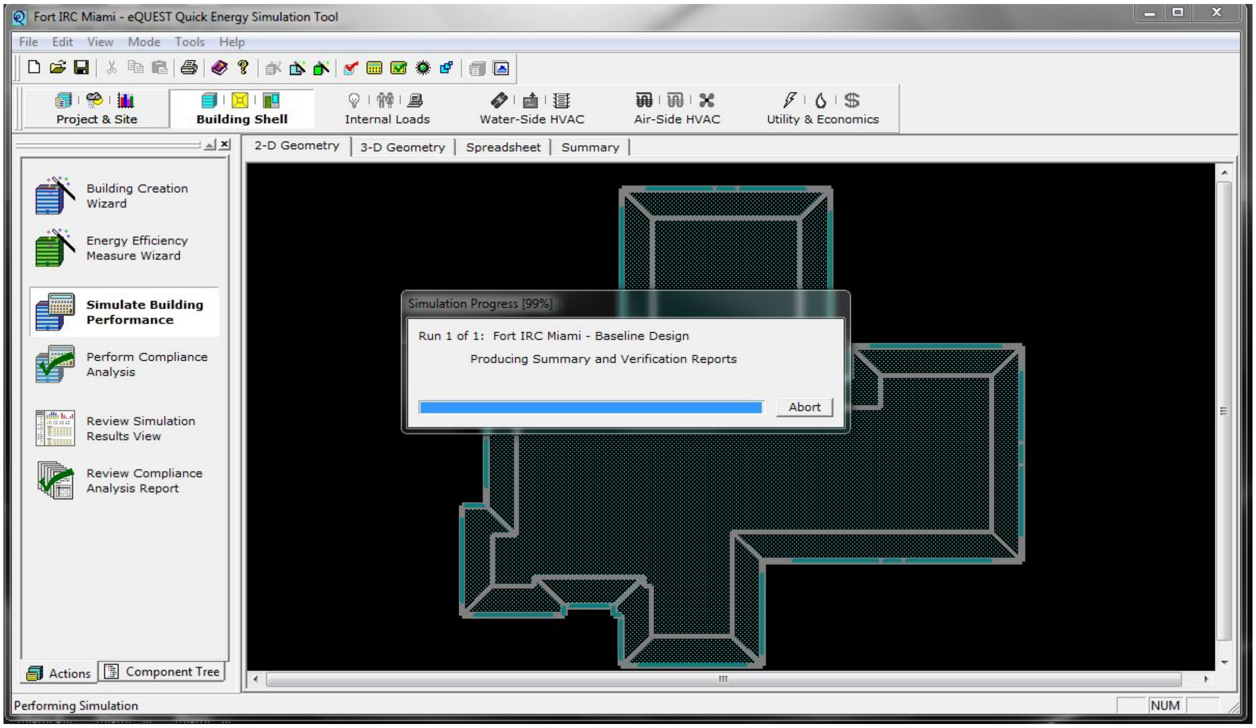

Figure C 1. An eQuest energy simulation being run in Miami to get the building load.

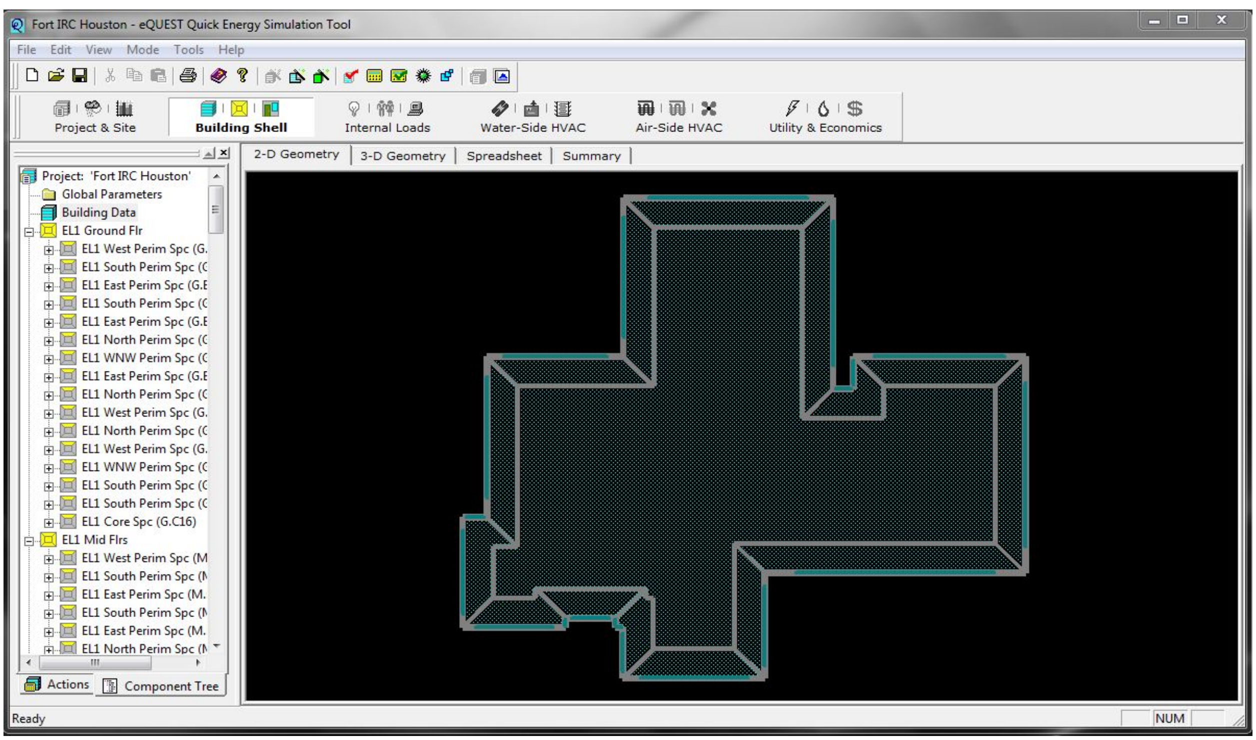

Figure C 2. A 2D eQuest model of the building in Houston.

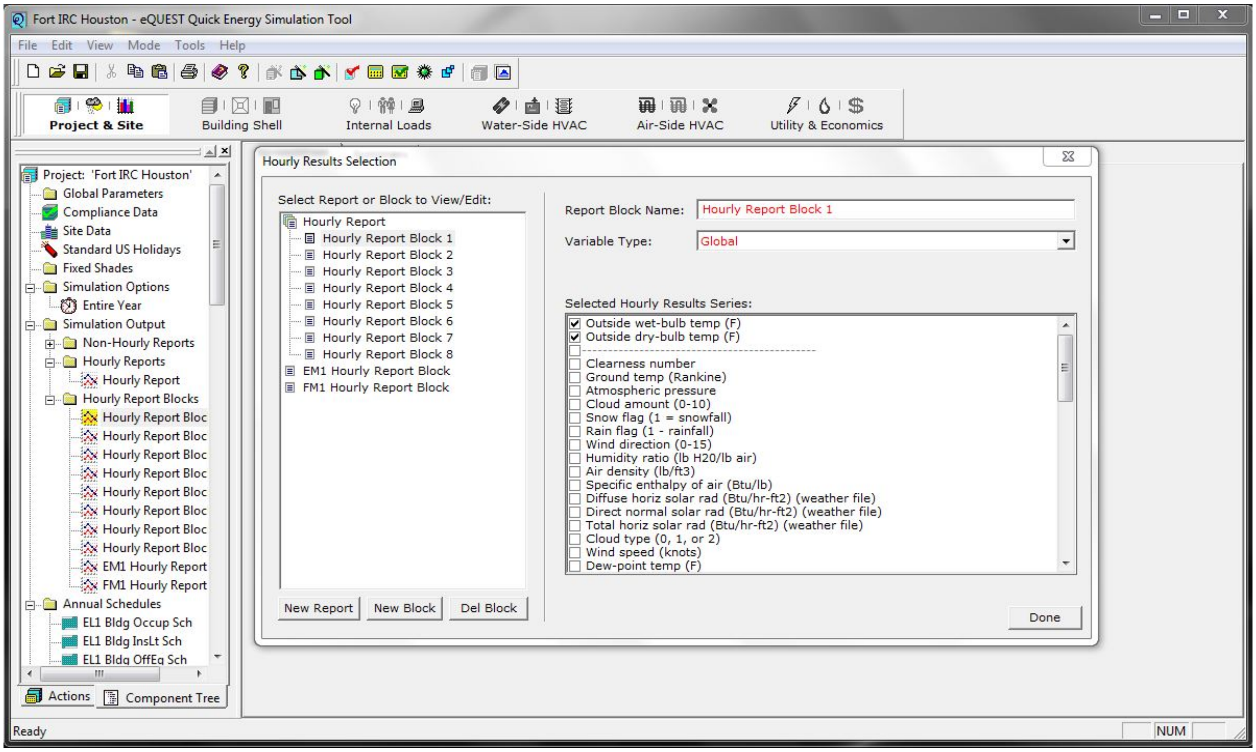

Figure C 3. The hourly selection options for the building in Houston.

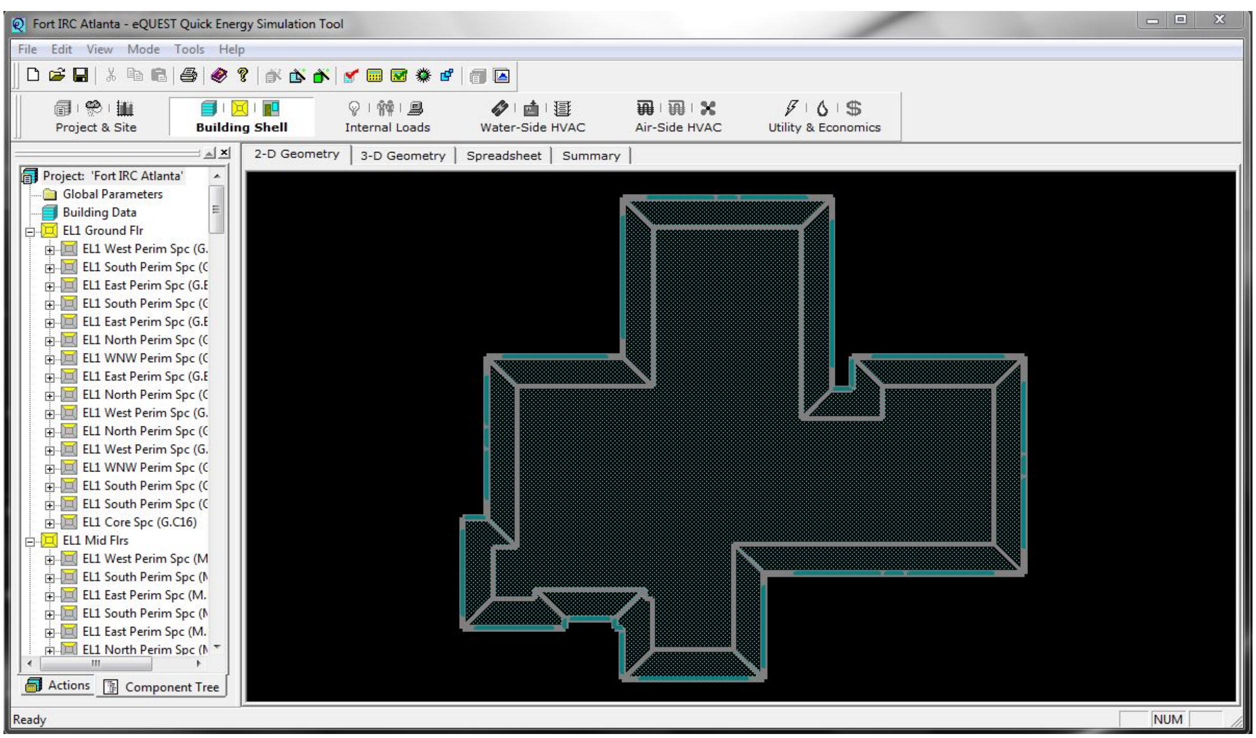

Figure C 4. A 2D eQuest model of the building in Atlanta.

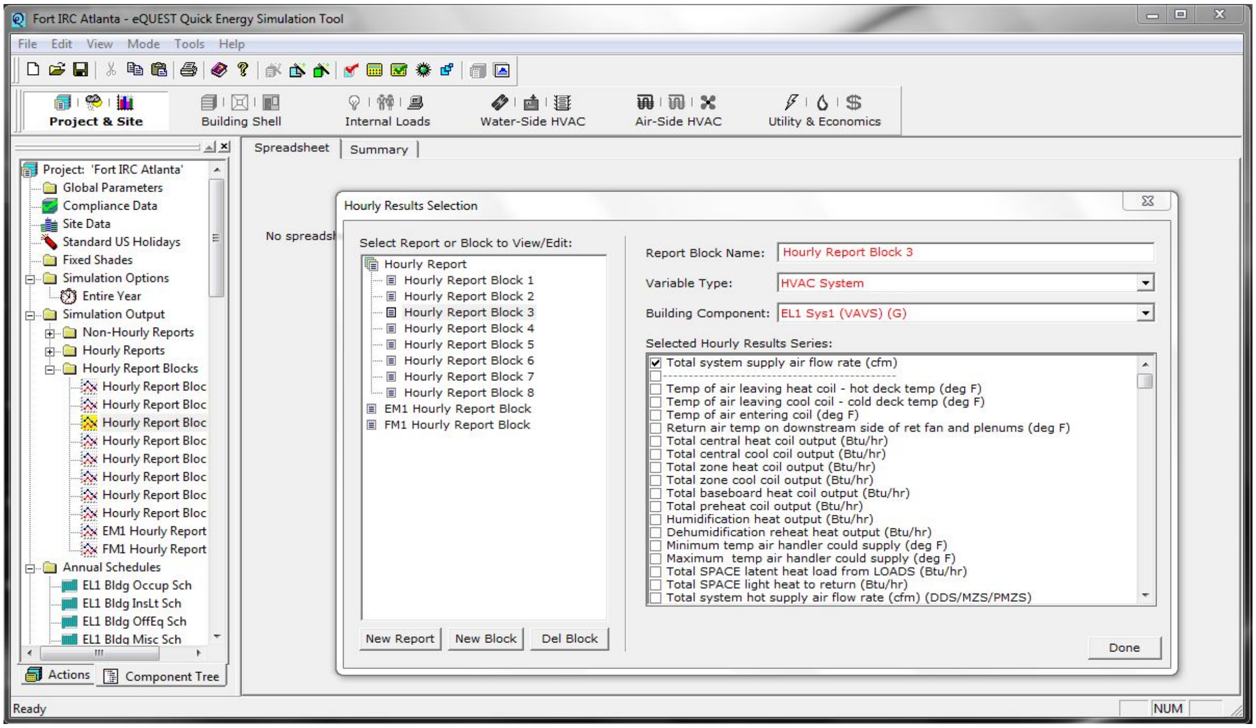

Figure C 5. The hourly selection options for the building in Atlanta.

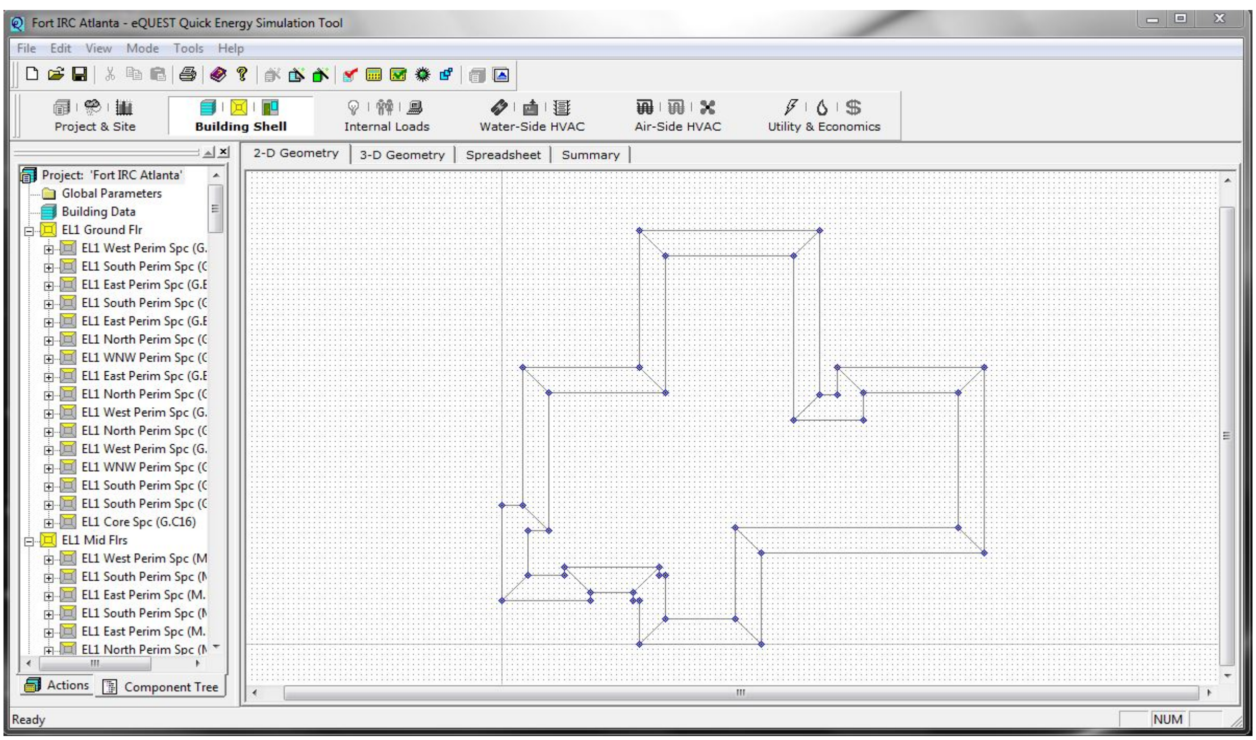

Figure C 6. The building drawn into the eQuest software.

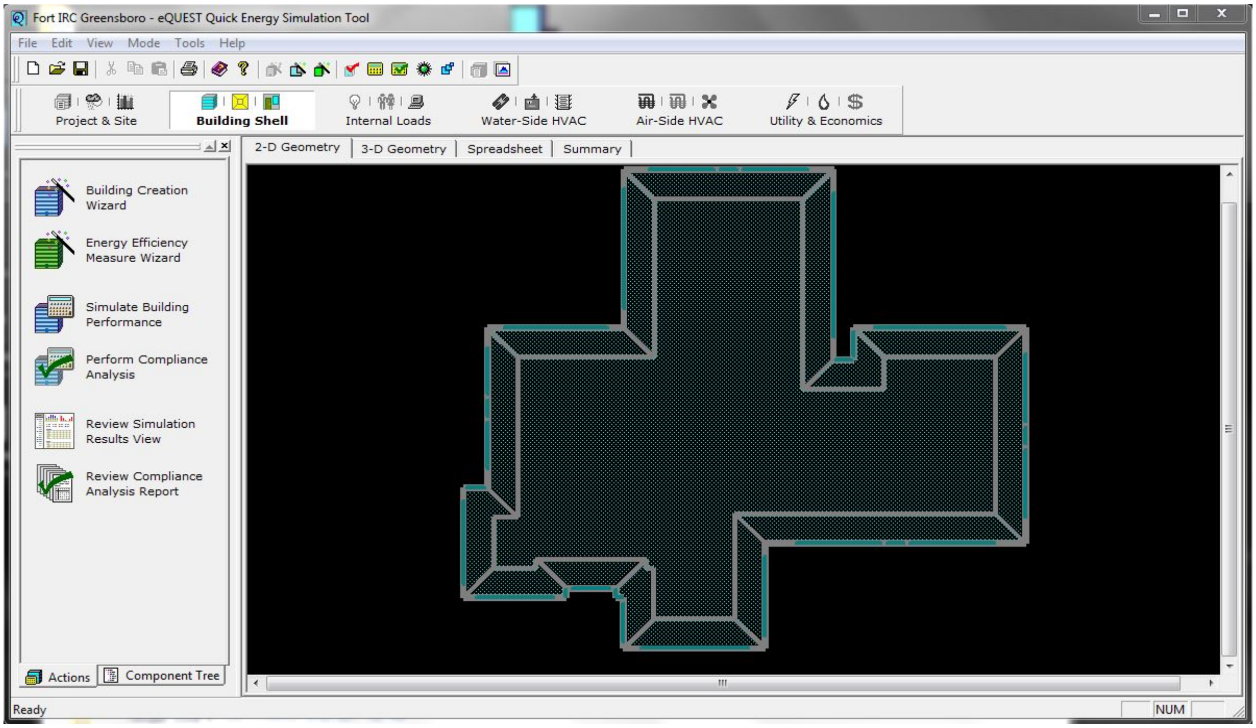

Figure C 7. A 2D eQuest model of the building in Greensboro.

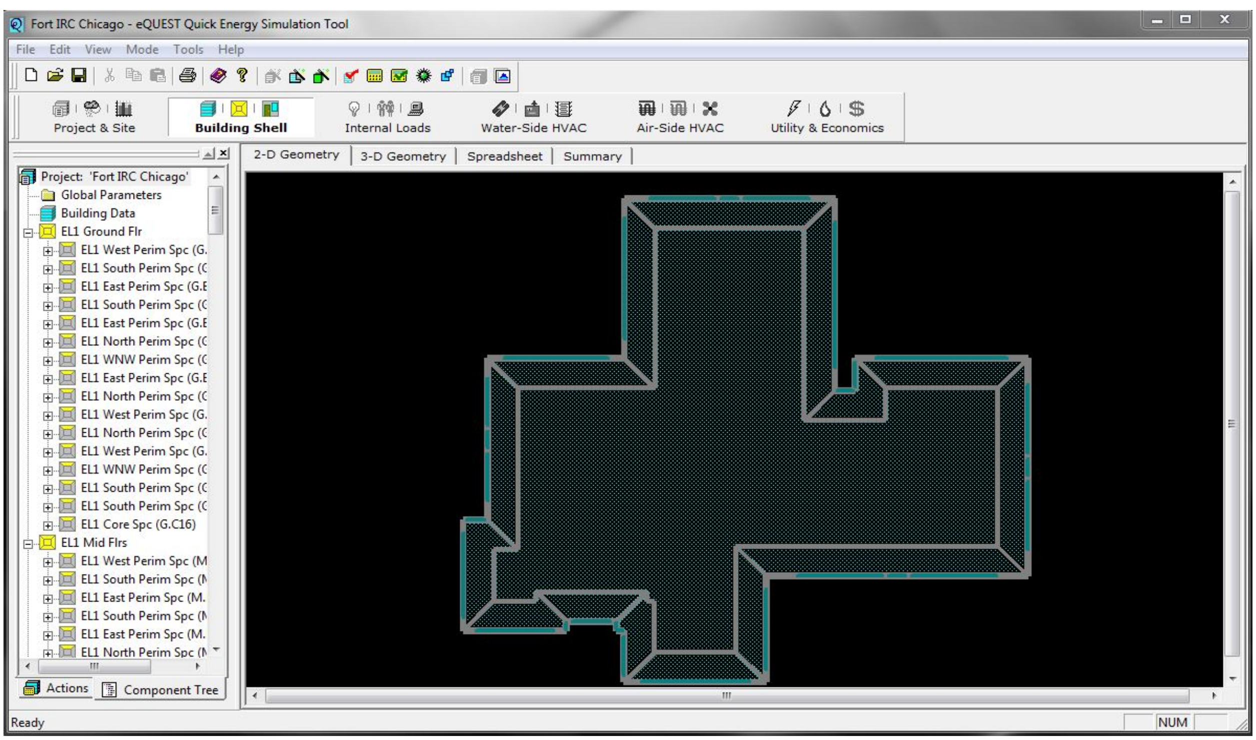

Figure C 8. A 2D eQuest model of the building in Chicago.

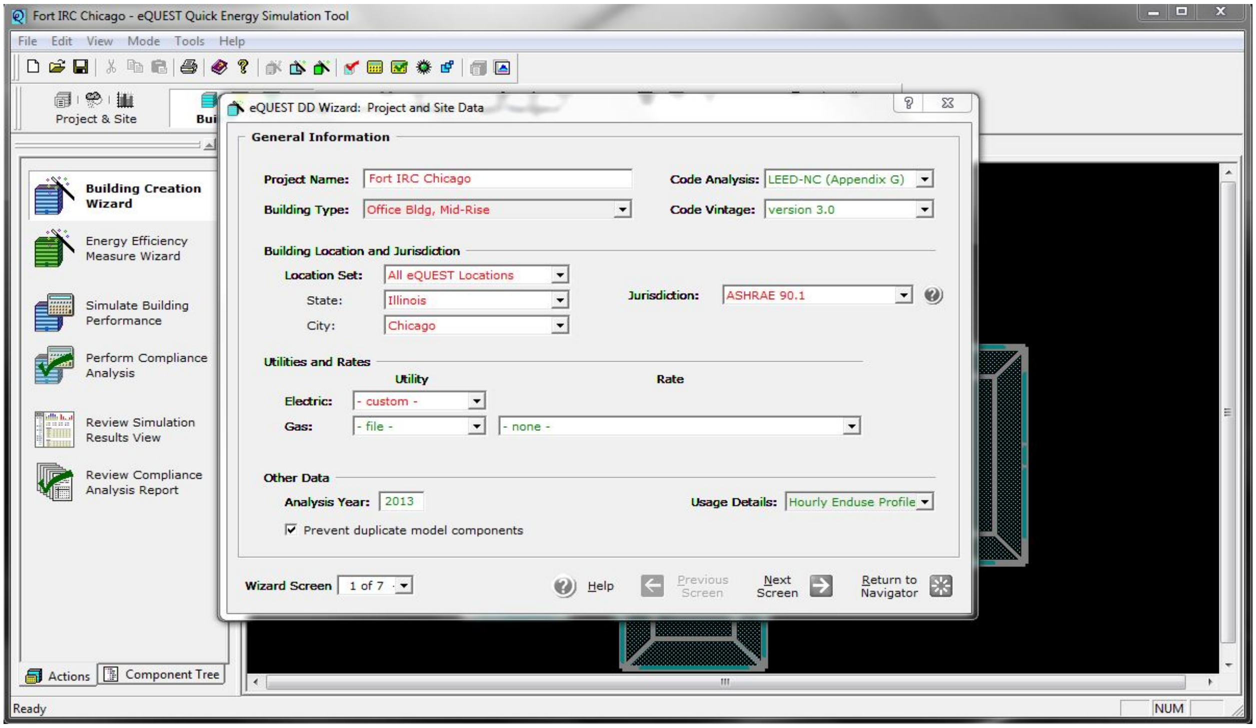

Figure C 9. The project and site data options in eQuest.

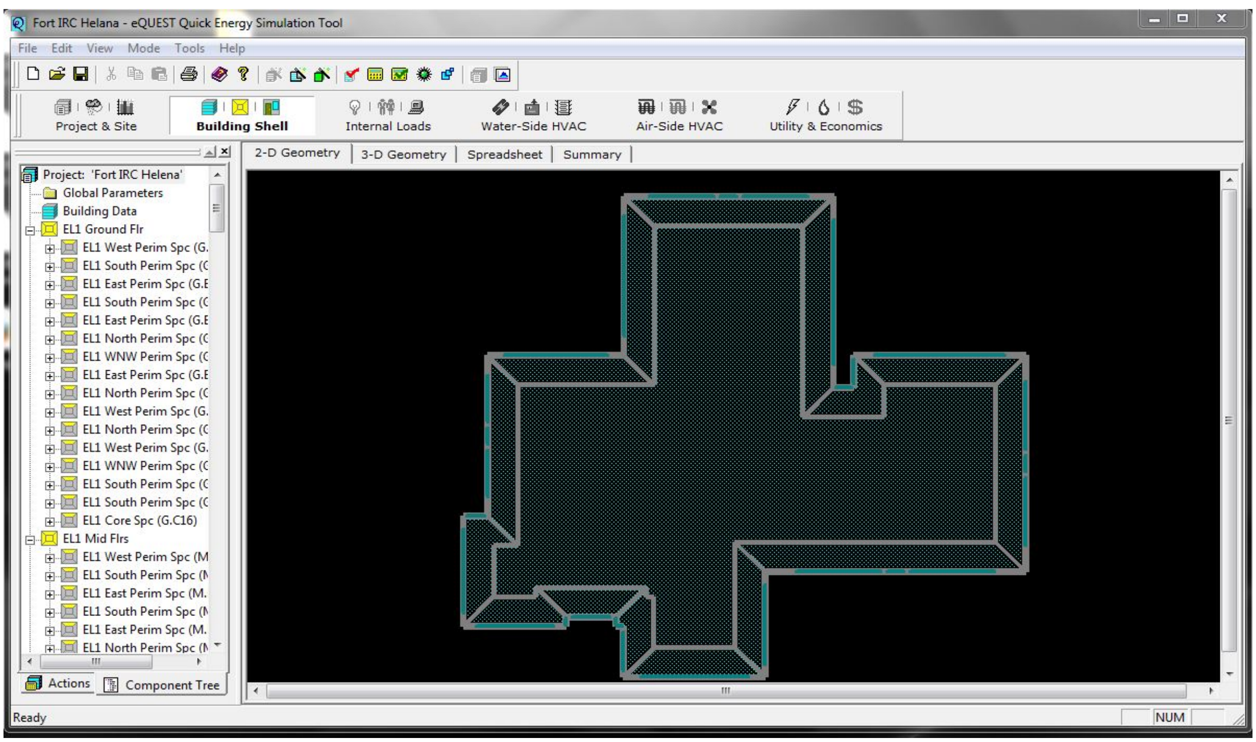

Figure C 10. A 2D eQuest model of the building in Helena.

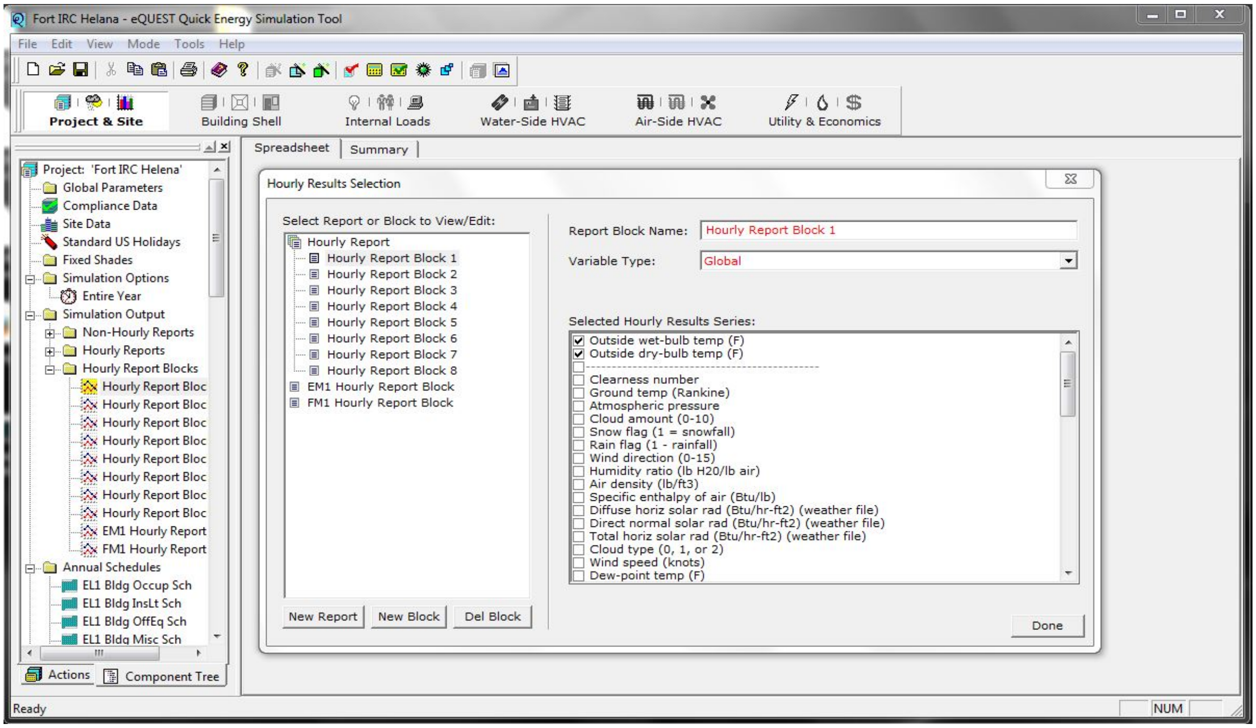

Figure C 11. The hourly selection options for the building in Helena.

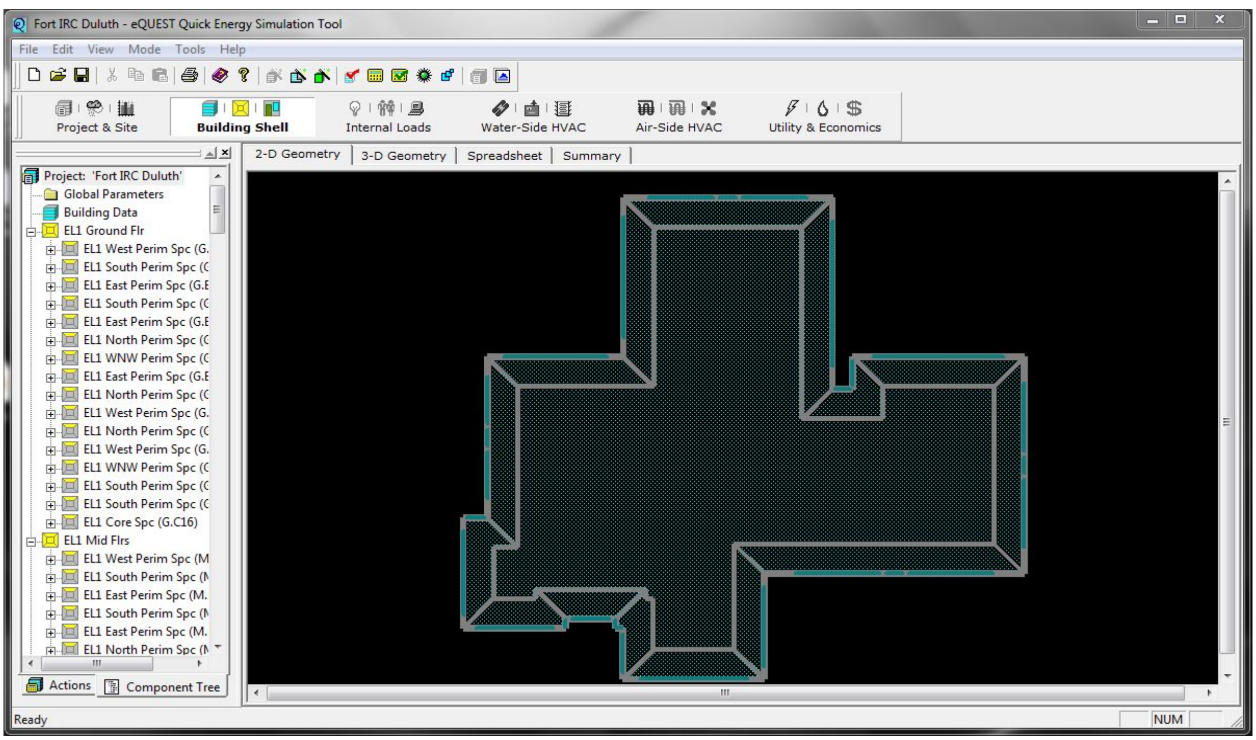

Figure C 12. A 2D eQuest model of the building in Duluth.

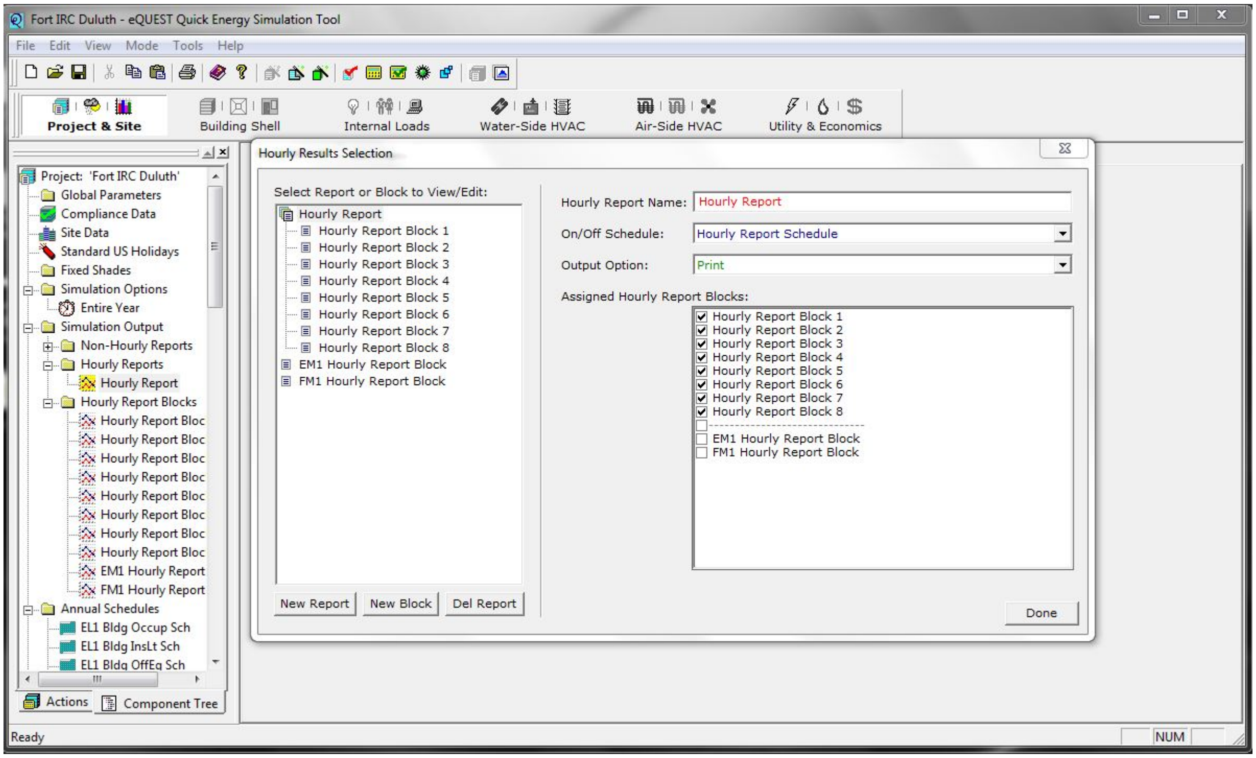

Figure C 13. The hourly selection options for the building in Duluth.

Appendix D

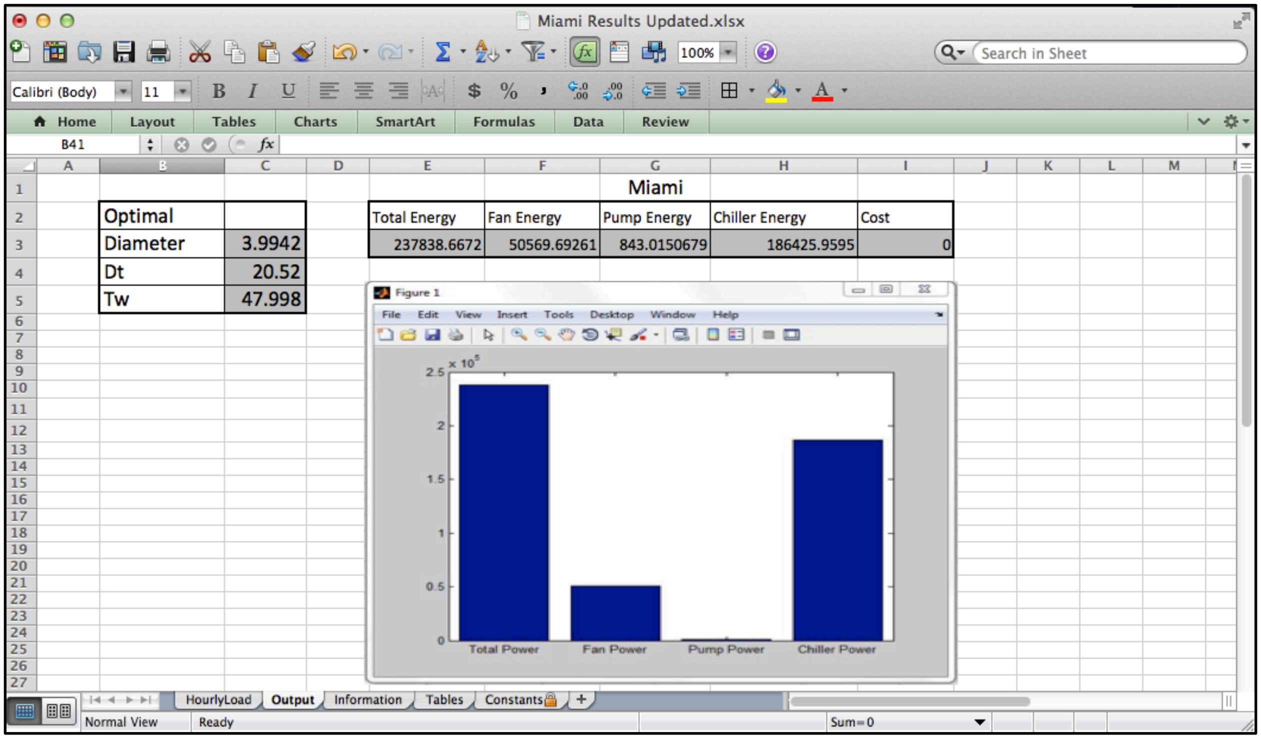

Figure D 1. The dual relationship with the optimization program in Excel and Matlab in Miami.

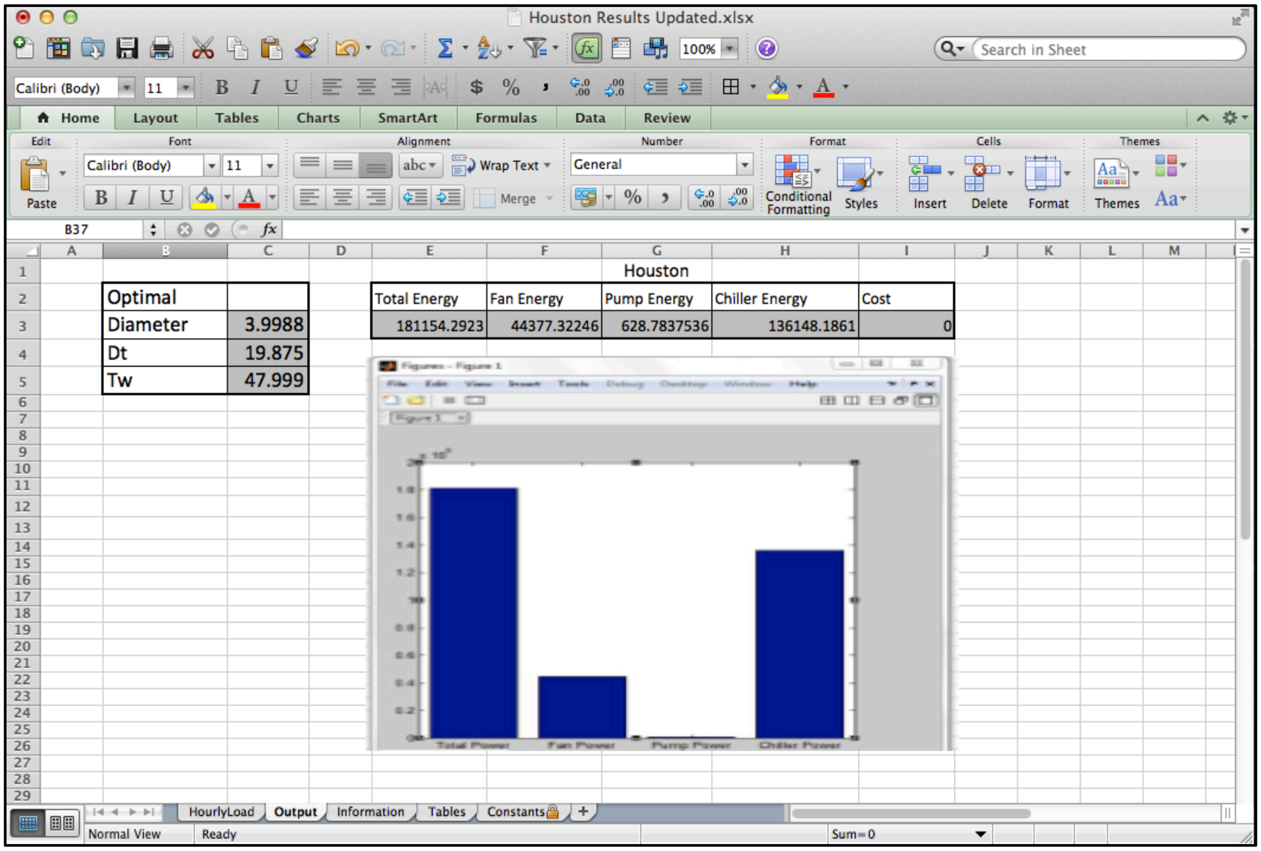

Figure D 2. The dual relationship with the optimization program in Excel and Matlab in Houston.

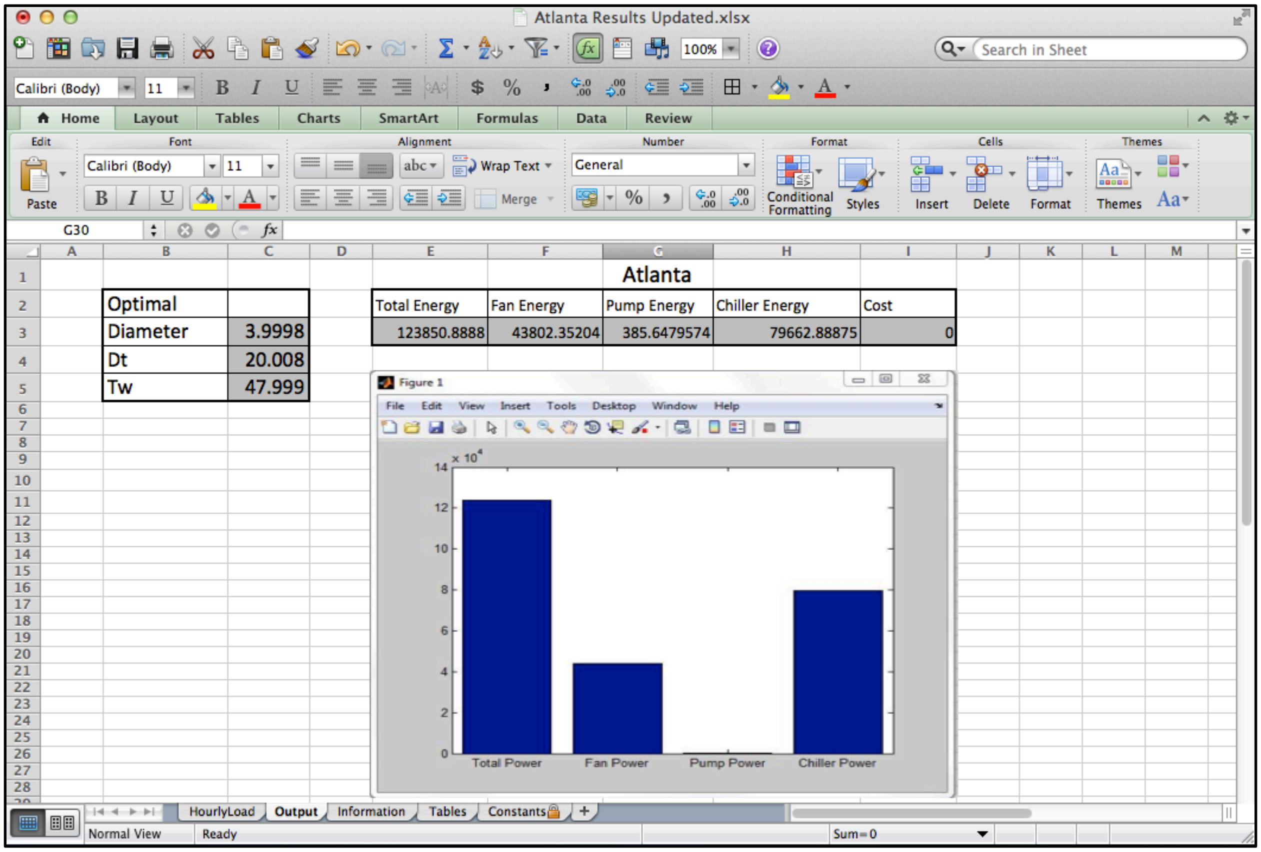

Figure D 3. The dual relationship with the optimization program in Excel and Matlab in Atlanta.

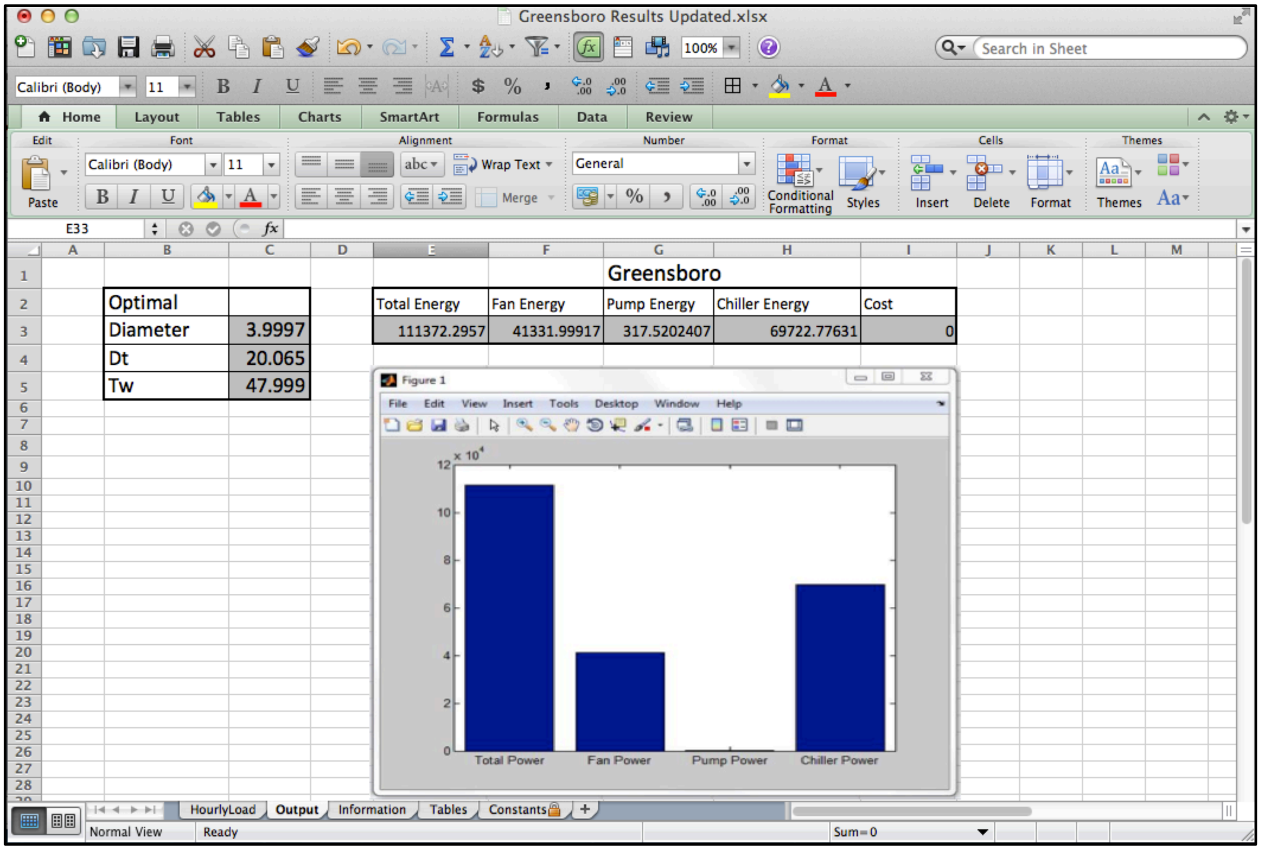

Figure D 4. The dual relationship with the optimization program in Excel and Matlab in Greensboro.

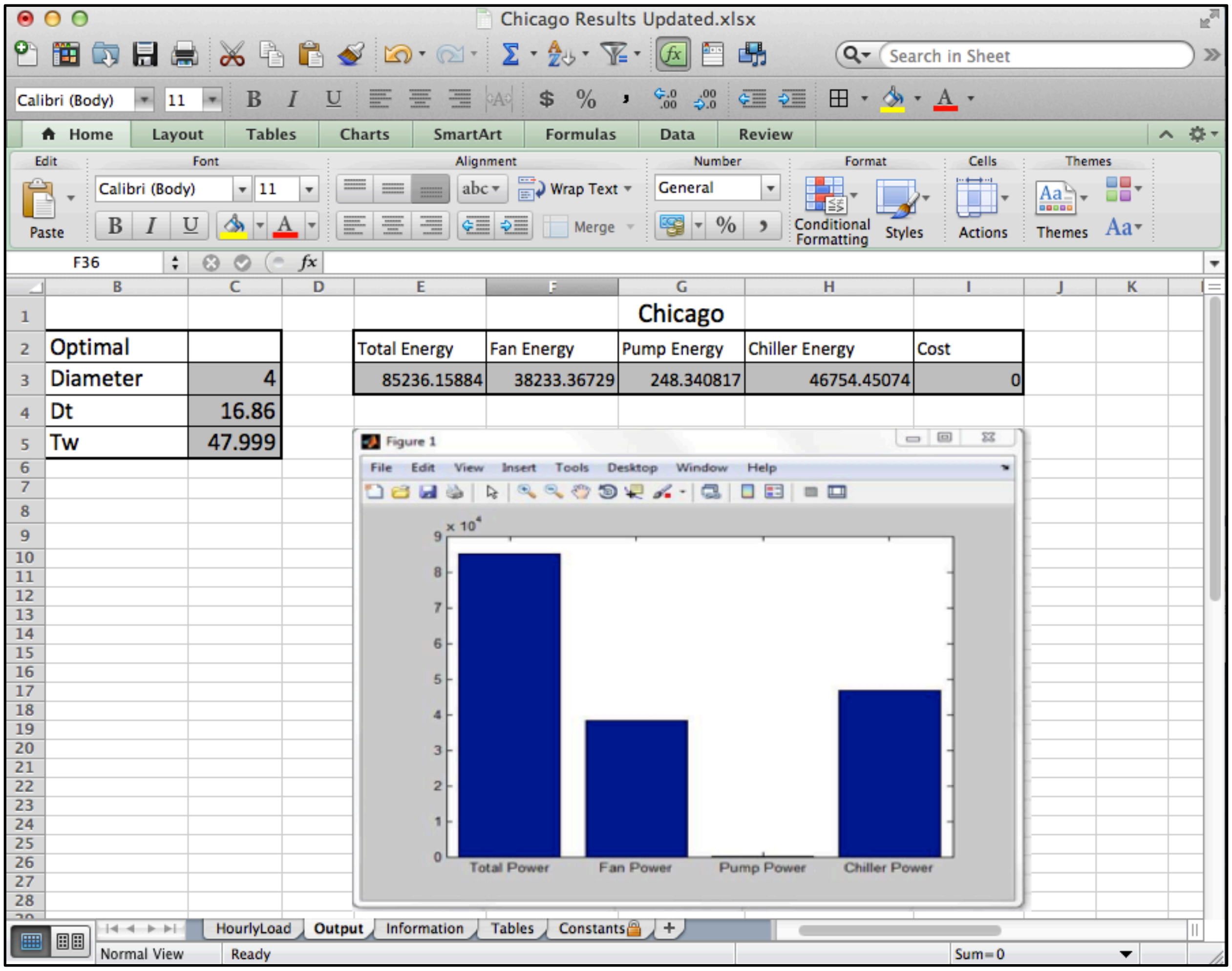

Figure D 5. The dual relationship with the optimization program in Excel and Matlab in Chicago.

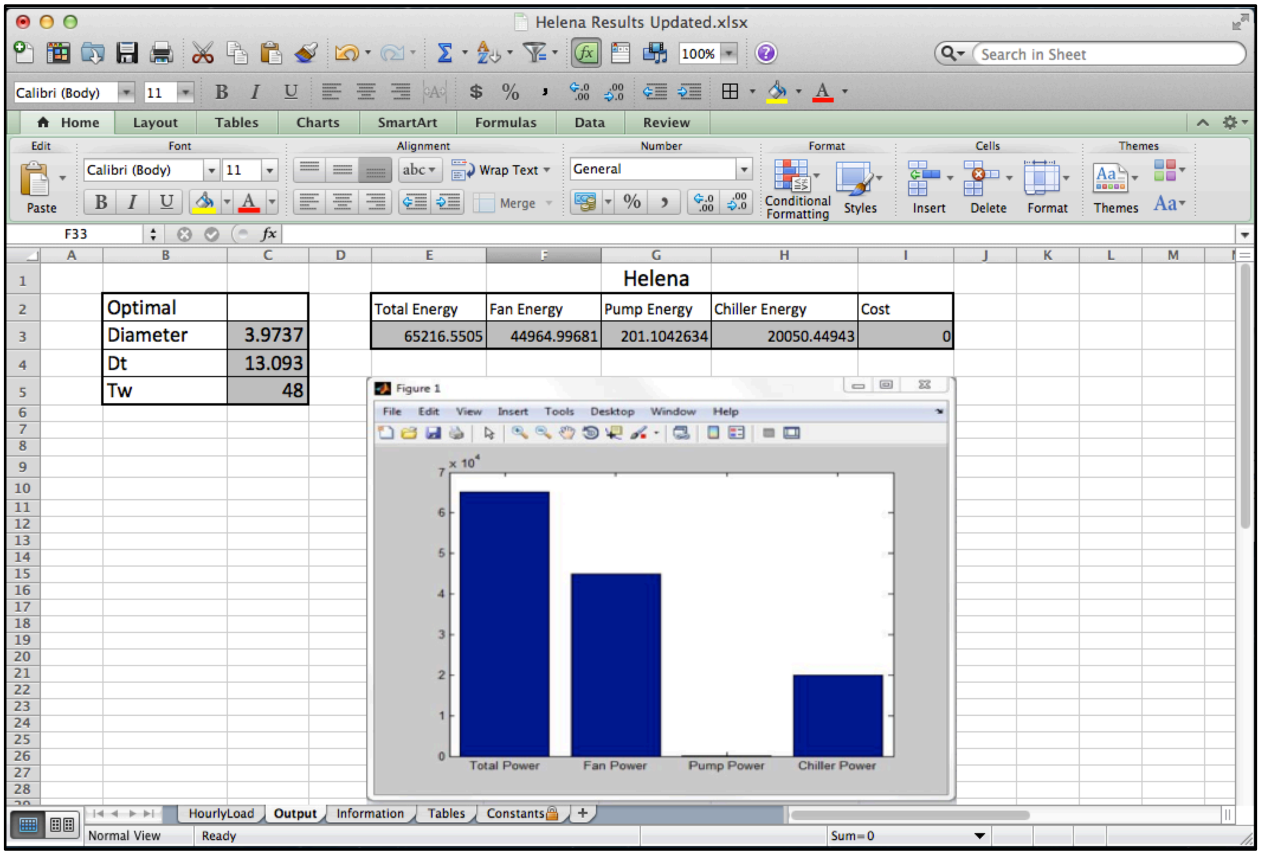

Figure D 6. This shows the dual relationship with the optimization program in Excel and Matlab in Helena.

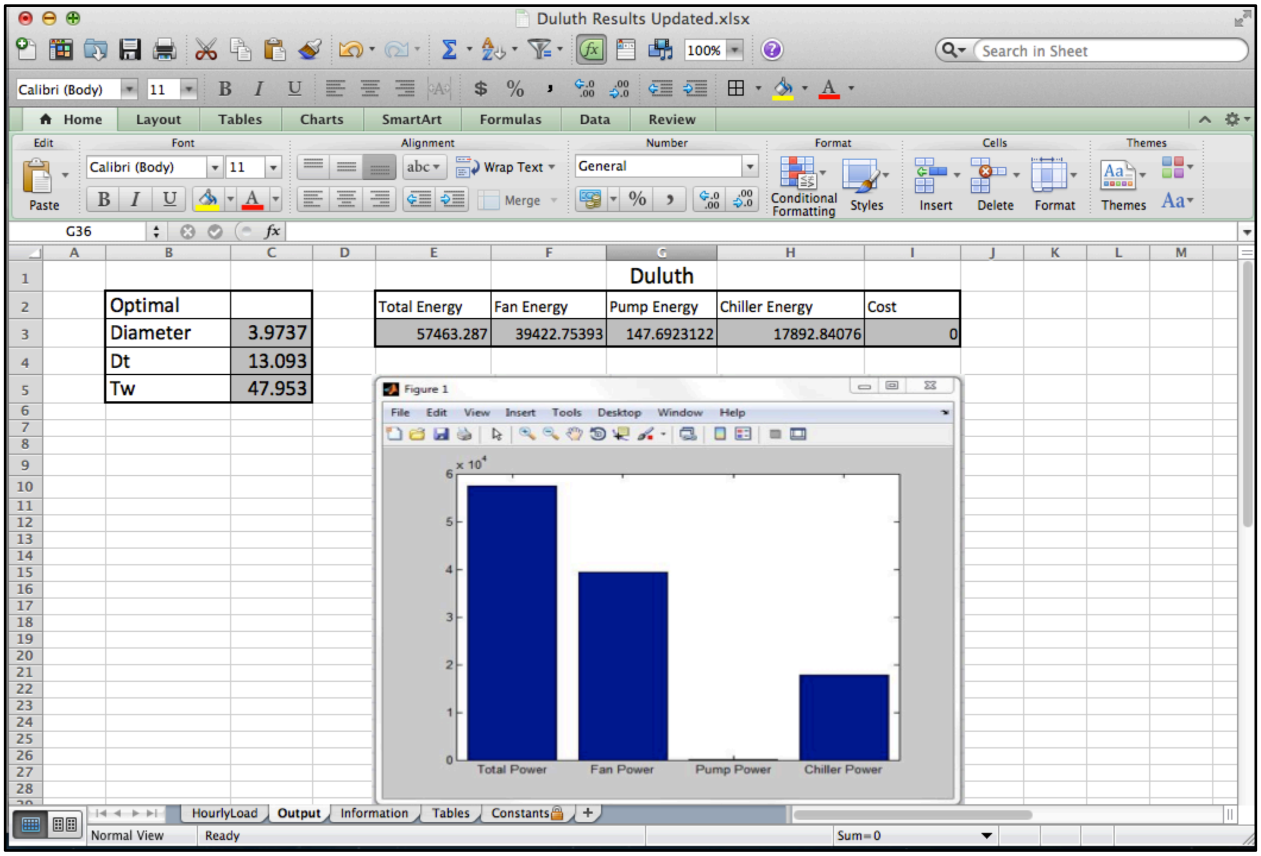

Figure D 7. This shows the dual relationship with the optimization program in Excel and Matlab in Duluth.